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## A STUDY FOR CREATION AND OPERATION OF PROTECTED POL STORAGE CAVITIES

Joe R. White

Daniel E. Pickett

Spencer J. Buchanan and Associates, Inc.

TECHNICAL REPORT NO. AFWL-TR-71-40

July 1971

AIR FORCE WEAPONS LABORATORY

Air Force Systems Command

Kirtland Air Force Base

New Mexico

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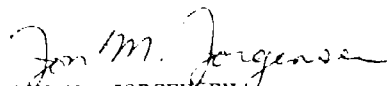
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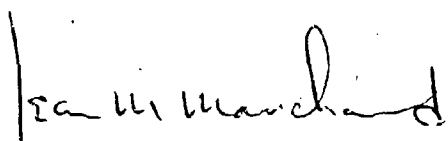
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ABSTRACT

(Distribution Limitation Statement B)

Existing United States Air Force petroleum product storage methods are either susceptible to conventional weapons effects or very expensive to construct. A safer, more economical method of storage is desirable. This report describes a study to determine the feasibility of creating underground cavities in clay type soils for storage of USAF petroleum products. Current underground cavity formation techniques were reviewed and evaluated. Research was conducted on experimental techniques, including chemical deaggregant and hydraulic methods, for creation of underground cavities. Cavity configuration, storage cavity innerliners, and cavity wall sealants were evaluated. Results of this study indicate a hydraulic technique is adaptable to expeditiously creating, in clay soils, storage cavities which meet the needs of the United States Air Force. Petroleum products would be stored within an innerliner placed inside the underground cavity. It is recommended that operational tests, including actual construction of three cavities, be initiated.



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# ABBREVIATIONS AND SYMBOLS

A	Nozzle cross-sectional area, cm <sup>2</sup>
F	Reaction force, lb
H <sub>o</sub>	Height of cavity, ft
J	Joules
P	Stagnation pressure, psi
P'	Output horsepower, hp
S <sub>h</sub>	Horizontal stress, psi
S <sub>v</sub>	Vertical stress, psi
V	Jet velocity, fps
V <sub>c</sub>	Cavity volume, ft <sup>3</sup>
W	Yield, kilotons
W <sub>o</sub>	Width of cavity, ft
g	Gravity (32.2 ft/sec <sup>2</sup> )
h	Depth of burst, ft
h'	Vertical distance below surface, ft
k	Liquid compressibility factor
m	Ratio of horizontal to vertical stress
p	Average overburden density, gm/cc
p'	Jet Density, pcf
p''	Water pressure, psi
γ	Unit weight of rock
μ	Poisson's ratio
σ <sub>t</sub>	Tangential stress
σ <sub>t</sub> /S <sub>v</sub>	Stress concentration
σ	Constant for rock medium

## SECTION I

### INTRODUCTION

The problems encountered with protecting stored POL (petroleum, oils and lubricants) products against nonnuclear weapons effects are numerous and of continual concern to the military engineer on operational bases throughout the world, particularly in Viet Nam, Thailand, and Korea. One of the primary methods of storage is utilization of above-ground steel tanks; however, these are subject to attack by fragmentation weapons which can result in leaks and ignition of the spilled POL product. Collapsible containers (bladders) are used, but they provide protection only by dispersion and they have relatively small capacities. Underground concrete tanks are less vulnerable to attack but their construction is costly and time consuming.

For the military engineer who is faced with meeting operational requirements in a minimum of time, the rapid safe formation of storage and disbursement facilities is of paramount importance. The primary concern is that POL products be stored safely, not exposed to contaminants, and easily accessible for removal and distribution from the storage facility. By proper utilization of underground cavities of controlled sizes and shapes created in soil formations, these requirements can be satisfied.



## SECTION II

### OBJECTIVE

The objective of this study is to analyze the feasibility of existing and experimental techniques for creation of underground storage cavities as applicable to United States Air Force requirements for POL product storage.

An evaluation was made of current underground cavity formation methods including drilled and underreamed shafts, conventional tunneling and excavation, solution mining, and both conventional and nuclear explosives. Such a comparison involved a study of the technical advantages and disadvantages of the various methods, appropriate economic analysis, and review of safety and construction considerations.

Research was conducted of experimental underground cavity formation techniques including chemical deaggregant and hydraulic methods. Evaluation of the applicability to United States Air Force requirements necessitated investigation of cavity configuration, bladder (innerliner) information, possible cavity wall chemical sealants, and soils data from the designated storage areas.

### SECTION III

#### AIR FORCE POL STORAGE METHODS

The United States Air Force currently uses three primary methods for bulk storage of POL products. These are steel tankage, concrete tankage, and collapsible containers. A number of variations, such as underground systems, are applicable to each method.

##### 1. STEEL TANKAGE

POL products are normally stored in conventional steel tanks at most permanent installations. Steel tanks may be constructed either above or below ground surface, and the interior is usually unlined. Connections for the tank shell components at permanent installations may be riveted or welded, although welded connections are preferred. Tanks are principally cylindrical or rectangular in configuration and may be placed either vertical or horizontal; however, tanks with a capacity in excess of 500 barrels are usually cylindrical shaped in the vertical position. Horizontal tanks are normally small. Roofs for vertical tanks may be of the cone, lifter, or floating variety. Sizes range from 100 to 10,000 barrels capacity.

Bolted steel tanks are normally used for semipermanent or temporary storage. These have a greater speed of field erection and can be dismantled and moved to a new location if necessary (Ref. 1). Bolted type steel tanks are shipped overseas in the disassembled condition.

Normal pumping or gravity methods are employed for loading and unloading the tanks. Above-ground tanks are usually surrounded by a soil dike or berm to prevent accidentally spilled products from spreading.

Steel tank storage systems constructed underground are less susceptible than above-ground facilities to damage from sabotage or nonnuclear weapons effects.

One variation of the underground steel storage tank is the antiquated hydraulic (aqua) system. This was a dispensing facility formerly used for the safe, efficient handling of aviation gasolines. Operations were based on the principal that aviation gasolines are lighter than water and do not mix with water. Water pressure, rather than pumping equipment, was used to transfer fuel. There was no evaporation loss and explosion hazard was eliminated because no air spaces existed for accumulation of fumes. Positive operational control prevented water from entering the distribution line. This system was not used for jet fuel because the specific gravity was too similar to that of water and the fuel does not separate readily from water. This system, being completely contained underground, was protected from projectiles or blasts. Currently, there are no aqua systems being utilized for storage of Air Force POL products.

## 2. CONCRETE TANKAGE

Although a variety of shapes and designs of underground concrete storage tanks for petroleum products may be constructed (Ref. 2), the rectangular and cylindrical tanks are the most common. Roof supporting columns are strategically located inside each tank to lend support to the heavy concrete slab that forms the tank roof. The majority of underground concrete fuel tanks at permanent military installations are designed to have prestressed walls. Concrete tanks are usually lined or coated internally to prevent leakage and to provide a chemically inert barrier between the product and the tank surface. Characteristics of products

that are to be stored in a tank are used for determining the proper surfacing for the tank interior. Coatings such as sodium silicate (Ref. 2) are used to prevent contamination and seepage of jet fuel.

Of the three primary storage methods now in use, properly constructed underground concrete tanks are least vulnerable to nonnuclear weapons effects. Obviously, the use of concrete storage tanks is limited to permanent or semipermanent installations, and is not adaptable to POL storage during field operations.

### 3. COLLAPSIBLE CONTAINERS

Collapsible, portable tanks are designed for the temporary storage of liquid fuels in military operations (Ref. 3). The cell of the container is constructed of light weight fabric impregnated with petroleum resistant synthetic rubber. The light weight and compact packaging of the collapsed containers facilitate their transportation in the field by truck, car, rail, or air. The cells range in capacity from 500 gallons to 10,000 gallons. Access holes covered with metal closure plates are provided for any necessary inspection, cleaning, and internal repair. Inlet and outlet fittings are provided for hose connections used in filling and dispensing the stored product. Pumps are normally used for filling and emptying the container. Kits are provided for repair of minor damage such as punctures. If containers are installed in quantity, adequate spacing and dikes are provided in order to minimize the danger of fire.

Although quickly and easily installed, these collapsible tanks are particularly vulnerable to sabotage and the effects of most conventional type weapons.

## SECTION IV

### CURRENT UNDERGROUND CAVITY FORMATION METHODS

There are currently a number of methods for creating cavities in subsurface strata. These techniques employ large diameter shafts and drilled and underreamed shafts, conventional tunneling and excavation, solution mining, conventional explosives, and nuclear explosives. Some of these techniques are frequently utilized for storage of various POL products while others seldom function for storage cavities.

#### 1. LARGE DIAMETER SHAFTS AND DRILLED AND UNDERREAMED SHAFTS

The use of large diameter vertical holes and/or drilled and underreamed shafts has been greatly expanded since 1950. Large diameter shafts usually infer constant diameter vertical holes in excess of 30 inches diameter; whereas, drilled and underreamed shafts refer to enlargement, at the desired depth, of an access bore hole by means of an underreaming tool. Large diameter holes have been drilled for underground storage chambers and mine access shafts, rescue shafts, water wells, drilled piers, missile silos, inspection shafts, and emplacement of nuclear explosives. Drilled and underreamed holes have been used extensively for construction of structural foundation footings which support axial loads. They have also been utilized for emplacement and testing of nuclear explosives.

The Atomic Energy Commission (Ref. 4) has conducted tests in large diameter rotary drilled holes with size ranges of 300 inches diameter to depths of 160 feet, 120 inches diameter to depths of 570 feet, and 72 inches diameter to depths of 4800 feet. Numerous other large diameter holes have been drilled to comparable sizes and depths. Underreams or "bells"

up to 180 inches diameter have been constructed at relatively shallow depths of less than 50 feet. The Atomic Energy Commission has used underreamed right cylinders at size and depth ranges of 16 to 42 inches and approximately 50 to 250 feet, respectively, in conjunction with underground explosion tests.

Currently, the four categories for construction of large diameter holes are churn drilling, auger drilling, calyx drilling and rotary drilling. The method applicable for a given situation is dependent upon the required hole diameter and depth, and the geologic condition of the material to be penetrated.

Advancing a hole by the churn drilling technique normally consists of dropping a heavy tool or bit attached to a wire line. The impact fractures the rock and soil which is subsequently removed from the hole by use of a bailer. Successive passes of specially constructed bits have been used occasionally to enlarge the hole (Ref. 4). Hole diameter is usually limited to 48 inches; however, hole depth and rock hardness do not appear to be limiting factors. The churn drilling technique is slow and cumbersome and seldom used.

The auger method is considered the most rapid and efficient technique for drilling large diameter holes of shallow depths (less than 150 feet) in soil type materials. The two primary types of augers are the bucket auger and the spiral flight auger. The bucket auger consists of a steel cylinder with a hinged bottom plate containing toothed slots. The flight auger consists of a single or double thread helix with fixed cutting teeth at the bottom. In auger drilling, the hole is advanced by rotating cutting devices attached to the bottom of the auger. The material is retained within the bucket auger or on the spiral auger and is removed from the hole

by pulling the bit to the surface. The maximum practical depth, as limited by the length of the telescoping kelly, is 150 feet. The two more common types of auger machines are the fold-over derrick unit and the crane suspended attachment machine. If operated within its limitations of size, depth, and geologic formations, auger drilling is relatively fast and economical.

Calyx drilling was the most common method for drilling large diameter holes in rock type materials prior to 1950 (Ref. 4). Calyx drilling is accomplished with a core barrel consisting of an inverted steel cylinder having short slots or teeth cut into its lower edge. Chilled steel shot is normally fed through the drill rods down to the inside of the cutting edge and is crushed below the edge of the core barrel. As the barrel is rotated, the angular shot fragments cut the rock. Fluid may or may not be circulated during drilling operations. The cuttings are caught in a calyx basket located immediately above the core barrel. The rock core is broken loose with wedges forced down one side. The core is then removed from the hole by drilling a small hole into the top of the core, inserting a wedge plug attached to a ring, and lifting with hoisting equipment. Removal of the core may require hand mucking if the material is highly fractured. Because of the cyclic nature of the operation, penetration rates are very slow.

Rotary drilling is currently the most widely accepted method for boring large diameter holes because formation hardness, depth, and diameter are not limiting factors. Rotary drilling is accomplished by using a rotary machine or table to transmit motion to a drill string which is equipped with a cutting tool or bit at the bottom. As the bit is rotated in the hole, the formation materials are broken into chips and removed by

circulation of a gas or fluid. The type of equipment necessary for rotary drilling of large diameter holes has been well documented (Ref. 4, 5). Basically, it is modified oil well rotary drilling equipment consisting of a power source, derrick, drawworks or hoisting mechanism, rotary table, casing, drill string, drill collars, bits, and circulating medium. The equipment is usually larger than oil well drilling equipment and drilling costs increase accordingly.

Underreaming (belling) devices are normally used in combination with either auger drilling or rotary drilling procedures. The use of underreams for foundation footings was begun in 1906-1910 by Mr. Willard Simpson Sr. in San Antonio, Texas. The first shafts were constructed by a mule-powered water well rig and hand belled by laborers. With the advent of power driven machinery, the equipment and technique have progressively advanced. The underreaming device used with auger drilling is equipped with extendible arms fitted with cutting teeth for enlarging and shaping the bottom of a boring. The cutting arms are forced outward from the bottom of the bucket by pressure from the weight of the kelly. As the bucket is rotated, a cone-shaped cavity is developed. The U.S. Waterways Experiment Station (Ref. 6) developed for the Atomic Energy Commission a rotary drilling tool capable of underreaming small spherical cavities. This tool has changeable compressed-air-operated (maximum pressure of 100 psi) blades having cemented carbide inserts. It was designed to cut rock formations that have about the same consistency and hardness of halite (ie. about 3 on Moh's scale of mineral hardness). Spherical cavity diameters were 24, 36, and 42 inches constructed in a 10-1/2 inch diameter access hole. The underreaming tool did not have the capability of removing cuttings. Therefore, it was necessary to drill a



"rat-hole" beneath the desired cavity depth and periodically blow the cuttings out with compressed air. The Waterways Experiment Station (Ref. 7) also developed a similar underreaming tool for constructing right cylinder cavities in halite.

Development of underground facilities for storage of Air Force POL products in large diameter straight shafts does not appear to be practical. The required size of construction machinery increases as hole diameter increases. Thus, it would take massive machines to construct a hole large enough for normal petroleum storage. Underreaming devices could be utilized only for very small capacity storage cavities. Access hole diameters must also increase with underream diameters. It would then become necessary to structurally bridge and plug the top of the access hole.

## 2. CONVENTIONAL TUNNELING AND EXCAVATION

POL products have successfully been stored in underground cavities, either naturally or conventionally mined, in rock formations such as salt, limestone, coal and clay. In addition, the "frozen ground" technique has been used for storage of liquid methane, and the "open pit - floating roof" technique has been used for oil storage.

Currently, the two principal methods of tunneling are drilling and blasting and the mechanical mole techniques. The drilling and blasting method includes many techniques which date back to early man when heating and water cooling were used to fracture hard rock. This method is necessarily slow and expensive due to the cyclic nature of operations. The more recently developed mechanical mole method permits a continuous removal of the tunnel heading rock. Mechanical mole equipment and techniques are being developed which permit rapid advancement of tunnels through a variety of subsurface strata, resulting in comparatively lower costs.

Procedures and techniques for the two primary tunneling methods have been well documented in numerous articles (Ref. 4). Fundamentally, the drilling and blasting procedures follow a cyclic operation of drilling blast holes, load and blast, ventilate, scale loose material from heading advances, muck out the blasted material, place structural supports, and advancement of drilling equipment for the next cycle. The number of blast holes required, the quantity and type of explosive, and the sequence of firing are controlled by the dimension of the bore and condition of the material being mined. The concept of boring machines or moles was utilized to start a tunnel under the English Channel in 1882 (Ref. 8). There are presently 20 makes of moles commercially available with many special features. The head of the mole consists of teeth or rollers (similar to rotary drilling rock bits) which are mounted on a revolving cutter wheel. As the cutter wheel rotates and advances, the rock is cut or spalled from the tunnel face. The excavated material is transported back down the tunnel and out to the disposal area. The advantages of mole tunneling as compared to blasting are as follows: 1) faster tunnel advance, 2) smooth, round, unshattered bores, 3) little overbreak, 4) less concrete lining, 5) less support required, 6) less rockfalls, 7) adaptable to continuous type system of operation, 8) less hazardous, and 9) less disturbance to surrounding facilities. Disadvantages include high initial cost of machine, excessive length of machinery "train," difficult to operate in mixed headings, and each machine is "tailor-made" for a specific project.

Warren Petroleum Corporation has mined a 650,000 gallon reservoir at its Breckenridge, Texas, plant (Ref. 9). A 4-foot square shaft was sunk to a depth of 223 feet through an upper limestone stratum at 175 feet and bottoming in a second limestone stratum at total depth. The storage cavity

was then formed by excavating approximately 100,000 cubic feet of shale between the two limestone layers. It has been reported that such installations should range in cost between \$2 and \$8 per barrel of storage, in unlined reservoirs of between 50,000 and 200,000 barrel capacity.

Abandoned coal mines have been put into limited use as storage cavities in several locations (Ref. 10). In this method, extensive care must be exercised to ensure that the POL product does not leak into other mine workings.

The "frozen ground" method is sometimes used for storage of liquid methane (Ref. 10). The earth around the periphery of an open excavation, which has an insulated cover, is initially frozen by liquid propane. The liquid methane stored in the excavation keeps the ground frozen and impermeable.

Another method of underground storage involves the use of open excavations covered with floating steel roofs (Ref. 11). Carlson notes an example in which Standard Oil Company of New Jersey has economically constructed an open pit reservoir in an abandoned slate quarry covered by a floating steel roof.

Professor Felix J. Kaisin, Consulting Engineering Geologist from the University of Louvain, Belgium, devised a technique for underground storage of LPG (Liquid Petroleum Gas) in Antwerp, Belgium (Ref. 12). In this method, a vertical mine-type shaft was excavated from the ground surface to a clay bed at a depth of approximately 230 feet. A number of horizontal tunnels were excavated in the clay by use of subway excavating equipment. These tunnels were lined with specially designed concrete blocks separated by wood and sealed for use as storage caverns.

The previously noted methods are not generally applicable to hasty creation of underground cavities for storage of small volumes of POL products. All these techniques are relatively expensive and the usage of each is limited to specific geologic conditions. The "frozen ground" technique apparently is applicable only to liquid methane storage. Also, storage in "frozen ground" and "open-pit - floating roof" facilities would be vulnerable to enemy attack.

### 3. SOLUTION MINING

Salt deposits have intrigued man since before the dawn of recorded history, and salt domes, specifically, have been the subject of scientific investigations for well over a century. In recent years, caverns have been dissolved in the salt, providing excellent and safe storage for a wide variety of volatile materials.

Although salt deposits have a world-wide distribution, salt domes are generally confined to low-lying coastal regions underlain by sedimentary rocks containing a thick salt layer typical of the formations found along the Texas Gulf Coast. Many thick beds of salt are found throughout the world.

All salt domes contain a central mass of salt which has been intruded into the overlying sediments. The origin of the salt mass is deep seated and of an obscure nature. However, it is believed that the high pressures prevailing at great depths caused the parent salt to become sufficiently plastic to enter regions of relieved pressure. The salt domes are usually covered by a cap rock of varying thickness and composed of a concentration of the less soluble constituents of the original salt deposit.

Early man used open-pit mining methods for extracting salt from very

shallow deposits. Salt is now obtained from underground deposits by two principal methods: 1) conventional underground mining and, 2) solution mining. Salt mines are conventionally excavated dry in a room-and-pillar operation by which salt is removed in a checkerboard pattern, leaving pillars for roof supports. In the solution mining process, the salt is dissolved by controlled circulation of fresh water and the saturated brines are pumped to the surface and subsequently processed. The brine from solution mining is the raw material in the manufacture of certain chemicals.

In the solution mining process, a concentric arrangement of different diameter pipes is used to introduce the fresh water and extract the saturated brine. The method of introducing fresh water into the salt stratum influences the circulation pattern, which in turn has a decided effect on the shape of the cavity formed. The methods for solution development of an underground salt cavity include: a) the conventional or bottom injection method whereby fresh water is introduced into the salt cavity at the bottom of the hole, b) the reverse circulation or top injection method whereby fresh water is introduced into the salt cavity at the top of the cavity, and c) variations to the conventional and reverse circulation methods whereby the number and positioning of the concentric pipe strings are altered. The salt is dissolved, producing a brine of a specific gravity approximating 1.2 which flows or is pumped up through the casing to the ground surface while the insoluble impurities settle to the bottom of the cavity. To prevent fresh water from dissolving the salt around the casing seat, an inert blanket of kerosene or oil is often maintained at the top of the cavity.

Reasonable control over the shape of a storage cavern is possible. However, in an effort to produce the desired cavity size and shape, a

number of variations to the basic solution mining process is utilized. These include the previously noted variation in arrangement of casing strings, method of introducing fresh water, position of inert buffer between the brine and the roof of the cavity, cross connection of two or more wells, hydraulic fracture of formations, and blasting.

The use of solution created cavities in salt for underground storage of liquid products has become increasingly important. This relatively recent method for storage was first used successfully in Canada during World War II. The materials being stored in salt solution cavities include low-pressure gases such as butane and propane, high-pressure volatiles such as ethylene, liquid petroleum products such as gasoline and crude oil, and radioactive wastes. Methods are now being refined for storage of natural gas, oxygen, and hydrogen.

The cost of dissolving storage cavities in salt depends on drilling costs related to depth, brine disposal problems, and varying capital equipment costs. It has been reported (Ref. 13) that the average cost of a 100,000 barrel cavity at a depth between 2,000 and 4,000 feet is slightly less than \$1.00 a barrel. This is less than one-half the cost of equivalent conventionally mined storage and about one-twentieth the cost of storage in above-ground steel tanks.

The advantages of salt cavity storage include lower costs, savings in ground space, savings in the use of steel, elimination of above-ground operation hazards, and bomb proof storage. This type storage is necessarily limited to geographic locations possessing a suitable saline formation. Also, creating relatively small storage cavities (1,000 to 5,000 bbl.) would not be economical. Therefore, this procedure is not considered practical for underground storage of POL at USAF operational bases throughout the world.

#### 4. CONVENTIONAL EXPLOSIVES

A secondary method which has received some consideration is the formation of cavities by the use of triple-stage conventional explosives in plastic clay formations. Researchers in the USSR (Ref. 14) have conducted successful field tests using conventional explosives to form cavities in clay. Field observations of this method showed it to be both quantitatively and qualitatively satisfactory for storage of fuels.

Formation of cavities in this manner requires detonation of successive explosions at approximately the same depth. Initially, a casing 12+ inches diameter is pressure grouted (cemented) into the upper portion of a drilled hole. A small explosion is first detonated, after which the drill hole is filled with water. This assists in containing subsequent explosions and ensures a more spherical cavity configuration, protects its surface from unnecessary fracture, and acts as a shock absorber to cushion the shock wave.

Subsequent explosions create the underground cavity (Figure 1, Ref. 14). The number of intermediate shots prior to the main explosion is dependent on the physical and mechanical properties of the soil and on the magnitude of the desired cavity. Two or three intermediate shots are normally considered adequate; however, a single intermediate explosion is sometimes sufficient. The final or main charge of larger magnitude is exploded to form the spherical chamber.

During the explosions, the soil is subjected to plastic flow and compaction, resulting in a cavity with a strong relatively watertight shell. The maximum increase in density of the clay approaches 40 percent of the initial density and decreases in proportion to the distance from the center by a linear relationship. Physical properties, such as unconfined com-

pressive strength and cohesion, increase by about four times after the explosion.

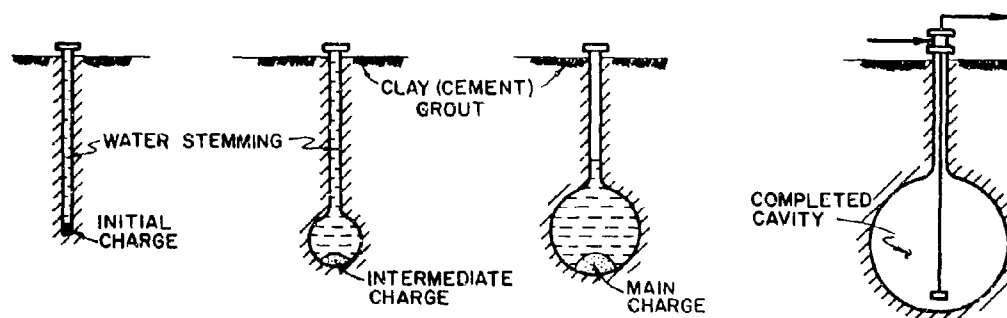


FIGURE 1. SEQUENCE OF FORMING UNDERGROUND CAVITY BY CONVENTIONAL EXPLOSIVES

The size of the resultant cavity depends upon the magnitude of the explosive charge and the compressibility of the geologic medium. The USSR researchers utilized charges weighing from 100 to 1,500 kg. (220 to 3310 lb.) at depths of 12 to 30 meters (40 to 98 ft). The largest cavities experimentally obtained by the USSR researchers had measurable volumes of 140 to 180 cubic meters (880 to 1130 barrels).

It is possible to form underground cavities in groups by utilization of charges exploded simultaneously or with millisecond delays. To exclude the influence of successive explosions in a cavity formed just previously, the total time of the delay must be less than or equal to the time of formation of the cavities. The time of formation of the cavity is a function of the physical and mechanical properties of the soil and



the weight of explosive charge.

The researchers filled three test cavities with fuel. Observation showed that storage in the explosively formed cavities was qualitatively and quantitatively satisfactory. It is our opinion that contamination of the stored fuel would result over a long period of time.

Estimated cost data were not available for this method of cavity construction. Among the possible advantages can be listed the following:

- 1) Stored products should not be affected by atmospheric temperature changes.
- 2) Only small quantities of metal would be required for construction of the complete system.
- 3) Underground storage could be provided where naturally occurring underground storage is not available.
- 4) Initial construction costs should be lower than costs for a cavity constructed by conventional methods.
- 5) The storage cavity would be protected from military attack.
- 6) Use of conventional explosives would exclude danger from radioactive contamination.

Several disadvantages are as follows:

- 1) Construction of this type cavity would be limited to areas containing relatively shallow geologic formations of the plastic clay variety.
- 2) The method is presently in the development stage and is highly theoretical.
- 3) Cavity would likely require a liner to prevent contamination of the fuel.

Research literature for the foregoing method is very limited. It is our opinion that this procedure merits further study and consideration.

## 5. NUCLEAR EXPLOSIVE METHODS

In recent years, underground storage of POL and gaseous products has

become increasingly widespread in the United States. The development of methods for underground storage of gaseous products has evolved primarily from the necessity for low cost - large capacity facilities. These are required so that the various suppliers can satisfy the customers seasonal as well as "peak day" demand fluctuations.

Under specified conditions, the underground method of storage has proved to be both economical and safe. One technique for creating these storage cavities is utilization of contained underground nuclear explosives. The primary explosive method utilizes, as a storage facility, the chimney created by detonation of a single underground nuclear explosion in impermeable rock such as shale.

Project Plowshare is an Atomic Energy Commission program established to investigate peaceful uses for nuclear explosives. One segment of the program was the Rainier shot in 1957 which was used primarily to study construction of underground oil and gas storage tanks. Project Ketch was another experiment designed to study the use of nuclear explosives in creation of underground gas storage cavities. It was developed by the combined efforts of Columbia Gas System Service Corporation, the Atomic Energy Commission, Lawrence Radiation Laboratory, and the United States Bureau of Mines.

The nuclear explosive is a compact and powerful source of energy. For cavity formation, nuclear explosives are generally placed underground in either tunnels or rotary drilled holes. When a nuclear explosive is detonated underground in rocks that are impermeable to water, the high temperatures and pressures which are generated vaporize and melt the surrounding rock. A spherical cavity is formed and the arch of the cavity usually collapses upward until the span is capable of supporting the overburden

through either beam or arch action. The resultant reservoir, technically designated as the chimney, is roughly cylindrical shaped and filled with rubble and void. At the bottom of the chimney is formed a solidified puddle of rock formed by the cooling, dripping and collecting of once molten rock. Surrounding the chimney is a zone of crushed and fractured rock of increased permeability (Figure 2, Ref. 15).

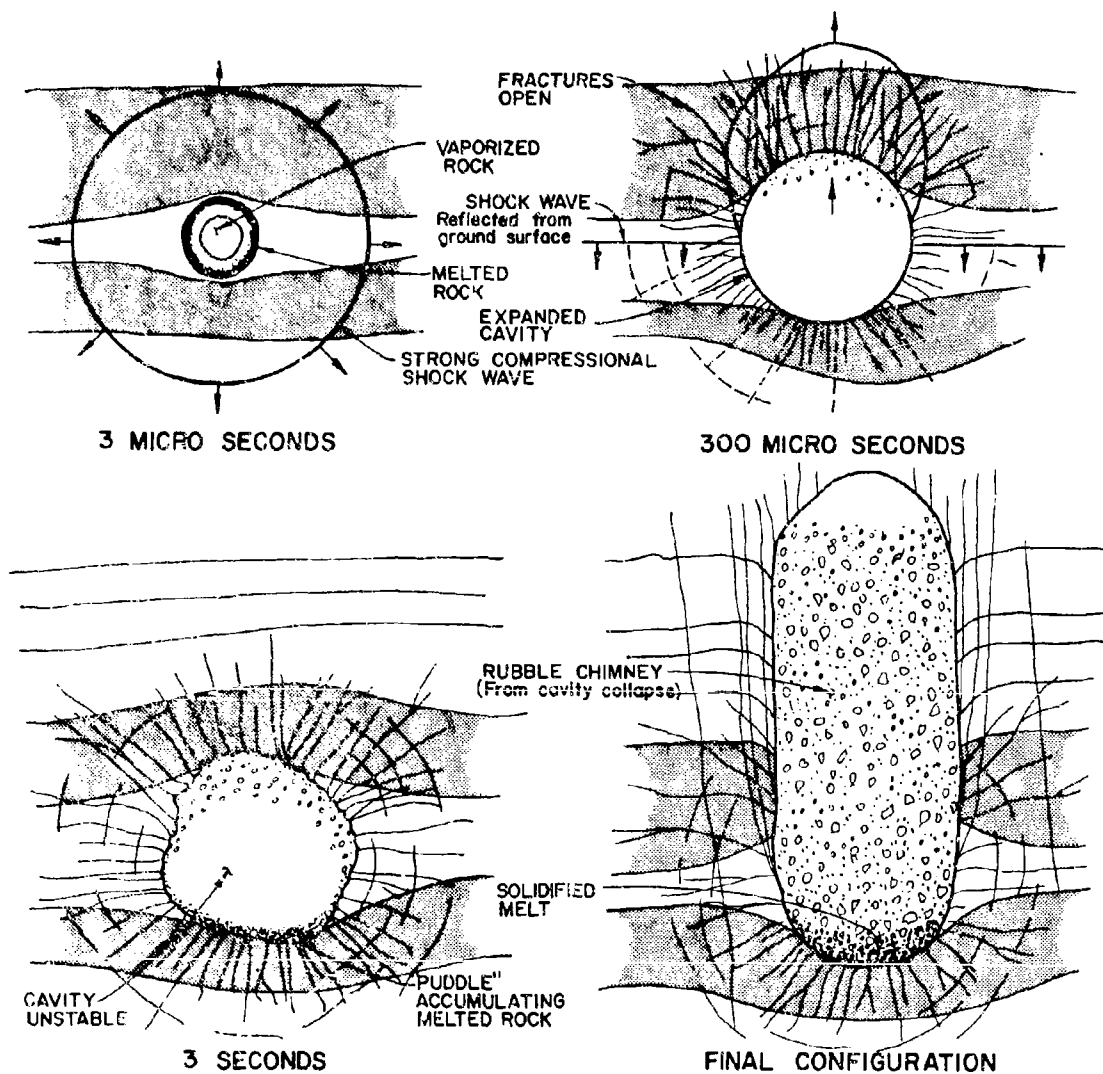


FIGURE 2. CAVITY-- CHIMNEY FORMATION HISTORY

The voids, or free intervals between the fragmented rock, comprise the storage capacity in the chimney. The resultant void volume is dependent upon the type of rock medium, depth of detonation and explosive yield. The gaseous product is stored within both the voids of the chimney and the fractured chimney wall rock.

In a contained nuclear explosion, there is no fallout or above-ground contamination. Some of the radioactive substances formed during the explosion are trapped in the essentially insoluble puddle. However, the top of the puddle and the chimney contain significant amounts of radiation which would be available for contamination of subsequently injected fluids. It would then be necessary to employ decontamination procedures in order to remove harmful radiation. Carlson (Ref. 11) has suggested the following methods: 1) A thorough flushing of the cavity with water, 2) store oil in the contaminated cavity and run through a mechanical filter upon withdrawal, 3) contamination could remain in oil. It could be removed at the refinery by disposing of asphalts after distillation.

The typical concept for injection and withdrawal of the stored product involves two wells as depicted in Figure 3 (Ref. 11). However, another concept utilizes only one well for both injection and withdrawal.

It has been reported (Ref. 15) that a 24-kiloton explosive detonated at a depth of 3300 feet in shale is expected to produce a chimney void volume of 2.2 million cubic feet and an additional void volume of 0.55 million cubic feet in the surrounding chimney wall rock. The chimney is expected to have a radius of 90 feet and a height of approximately 300 feet (Ref. 16). Cracks and fissures are expected to extend upward an additional 300 feet above the chimney.

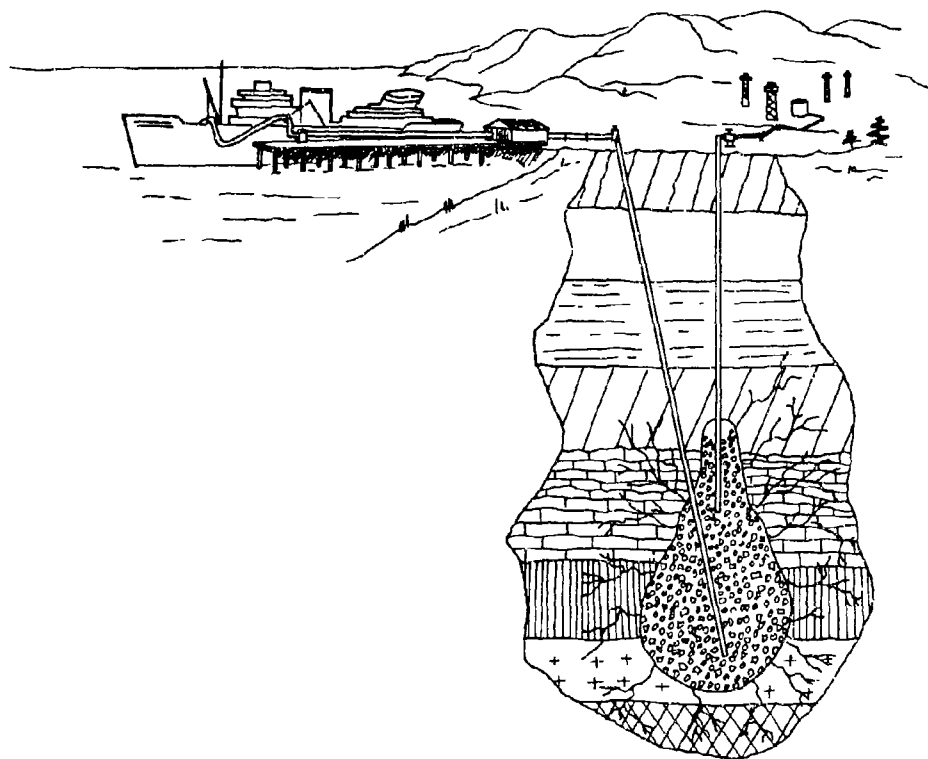


FIGURE 3. ARTIST'S CONCEPTION OF AN UNDERGROUND OIL STORAGE FACILITY CONSTRUCTED BY NUCLEAR EXPLOSIVES

The formula for chimney storage volume is:

$$V_c = \phi \frac{W (10^7)}{(ph)^{0.75}}$$

Where

- $V_c$  = cavity volume
- $\phi$  = constant for rock medium (estimated to range from 4.8 for dolomite to 17.0 for volcanic tuff)
- $W$  = yield in kilotons
- $p$  = average overburden density in g/cc
- $h$  = depth of burst in feet

Void volumes of five cavities were experimentally determined by Boardman and Taman (Ref. 16) and closely agree with the formula. Results are presented in Table I (Ref. 16).

TABLE I

MEASURED CHIMNEY VOID VOLUMES FOR FIVE EVENTS

MEDIUM	EVENT	YIELD (kt)	DEPTH OF BURST (ft)	AVERAGE OVERBURDEN DENSITY (g/cc)	CHIMNEY VOID VOLUME (ft <sup>3</sup> )
Salt	Gnome	3.4 ± 0.5	1184	2.3	1.0 × 10 <sup>6</sup> ± 10%
	Salmon	5.3 ± 0.5	2716	2.3	0.69 × 10 <sup>6</sup> ± 5%
Granite	Hardhat	5.4 ± 1.0	939	2.7	1.09 × 10 <sup>6</sup> ± 3%
	Shoal	13.4 ± 2.0	1205	2.7	2.87 × 10 <sup>6</sup> ± 8%
Dolomite	Handcar	12.0 ± 1.0	1320	2.3	1.41 × 10 <sup>6</sup> ± 10%

As POL products are flammable care must be exercised in determination of cavity temperature before injection of the products. Temperature dissipation is dependent upon the moisture content of the rock medium. The cavity could be cooled by water circulation if necessary.

The Atomic Energy Commission is not currently authorized to supply nuclear explosives on a commercial basis. However, the AEC has published estimated charges for nuclear explosives which are sufficiently accurate for feasibility studies. A study (Ref: 11) was made comparing the costs of underground cavity formation by the use of conventional mining procedures and nuclear explosions. Results are presented in Table II.

TABLE II  
ESTIMATED SAVINGS RESULTING FROM USE OF  
NUCLEAR EXPLOSIVES OF VARIOUS YIELDS

Nuclear Explosive Yield	Estimated Cost of N.E. and Placement in Tunnel	Volume of Storage Cavity (bbl.)	Cost for Conventional Excavation of Storage Cavity	Estimated Savings by use of Nuclear Explosives
10 kt	$\$0.825 \times 10^6$	$0.7 \times 10^6$	$\$2.8 \times 10^6$	$\$1.9 \times 10^6$
100 kt	$\$1.25 \times 10^6$	$7.0 \times 10^6$	$\$28 \times 10^6$	$\$26.7 \times 10^6$
1 mt	$\$1.75 \times 10^6$	$70 \times 10^6$	$\$280 \times 10^6$	$\$278 \times 10^6$
10 mt	$\$2.0 \times 10^6$	$700 \times 10^6$	$\$2.8 \times 10^9$	$\$2.7 \times 10^9$

It is obvious that the nuclear explosive method has a substantial economic advantage over conventional excavation methods for formation of underground storage facilities.

The usefulness of a gas reservoir formed by an underground nuclear explosion is dependent upon the following items:

- 1) The chimney must contain the stored product at the desired pressure without leaking (Ref. 15)
- 2) The value of storage must be sufficient to justify the cost of creating it

- 3) There must be no significant radioactive contamination of gas that is delivered from the system
- 4) The nature of the reservoir must be such as to permit injection and withdrawal at an acceptable rate

Carlson lists another application for nuclear explosives in the oil-storage field. This method suggests the possible use of explosives for excavation of open reservoirs which would subsequently be covered with floating steel roofs (Ref. 11). However, contamination of the atmosphere and surrounding area is of primary importance in this application.

The underground nuclear explosive method of storage has a number of distinct advantages over conventional above-ground methods. These are as follows:

- 1) Lower initial construction costs
- 2) Stored products are virtually unaffected by ambient temperature changes
- 3) Construction doesn't require large quantities of metal
- 4) Provides large storage volume where naturally occurring underground storage is not available (Ref. 16).
- 5) Possible to produce stored gas over a wide range of flow rates with essentially the same equipment
- 6) Relatively low maintenance and insurance costs
- 7) Reduced probability of fires and other accidents
- 8) Storage facility can be easily camouflaged, resulting in greater safety from military attack

Among the disadvantages can be listed the following:

- 1) Impractical for relatively small volumes of storage at shallow depths
- 2) Nuclear explosives are not readily available to industry
- 3) Geologic conditions must be ideal
- 4) Possibility of radioactive contamination



- 5) This method of storage is presently highly theoretical and experimental

It is obvious that the advantages of cavities created by nuclear explosives apply to large volume storage and not to storage of relatively small volumes of POL products at operational bases, particularly in combat zones.

## SECTION V

### EXPERIMENTAL UNDERGROUND CAVITY FORMATION METHODS

Research of experimental underground cavity creation methods was primarily directed toward examination of the chemical and hydraulic methods.

Investigation indicated the latter of the two experimental techniques is currently receiving considerable attention from several sources and apparently has significant potential in future subsurface excavation.

Rock or soil disintegration is the key element in the overall excavation operation, determining in large measure the rate of progress and cost of the operation. Problems of disintegration or separation of rock or soil from its natural state usually increase with increases in strength of rock or soil. In addition to strength, natural flaws, toughness, abrasiveness and hardness of constituents and binders of rock or soil are important physical characteristics and, as they vary, the productivity and capability of present processes also vary.

Future excavation systems should extend the rock or soil disintegration at least one step beyond the obvious need to separate it en-mass from its natural condition, and this involves a method of pumping or transporting the rock or soil in as large sizes as possible. Normally the largest removable particle size is desirable, as excessive size reduction results in wasted energy.

A recent book by Maurer (Ref. 17) explores essentially all conventional and unconventional ideas for tunneling methods, from atomic energy to ultrasonics. His comparison of methods is phrased in the convenient term of "energy required to remove a unit volume of rock by the specific method

described." The unit for this value of "specific energy" is, by convention, Joules per cubic centimeter. For quick conversion  $100 \text{ J/cc} = 1 \text{ hp-hr/cu ft.}$

Since the role of energy delivered to rock or soil for excavation is to create surface (i.e., the finer the particles produced by the method, the higher the required specific energy), it is not surprising that specific energies vary widely: from 5,000 J/cc for rotary diamond drills to 4-10 J/cc for blasting. The higher value represents the probable upper limit for consideration of a new method, particularly if the energy form is expensive. Thus lasers which actually vaporize rock or soil are probably much too expensive to use unless the strength of a large volume of material could be reduced by application of a laser beam to a small volume, thereby perhaps allowing some hybrid process (laser/mechanical) to be developed. As discussed in the preceding section, blasting, which efficiently uses an inexpensive form of energy, is limited by the slowness of its cyclic nature.

Independent tests have been conducted in rock for various techniques including rotary drilling (water), explosives, lasers, electron beams, plasma, forced flame, chemical and other.

Three categories of comparison were:

1) Required Specific Energy (joules/cm)

May be considered the efficiency of the process

2) Maximum Power to Rock (Horsepower)

Amount of power physically placed against the rock by the process

3) Maximum Potential Drilling Rate

Determined by considering the efficiency and available power of the process

The data indicate the hydraulic technique has a drilling rate approximately five times greater than any other presently under development. Further, it permits applying large amounts of power to the rock face. For example, a water cannon can apply up to 2,000 horsepower to the rock face; whereas, electron beams and lasers are reportedly limited to a maximum of 10-24 horsepower respectively. A comparison of the maximum potential drilling rates in rock between hydraulic and other methods indicates the desirability of adaptation of the former for drilling and cavity creation.

#### 1. CHEMICAL DEAGGREGANT TECHNIQUE

The chemical deaggregant technique is an experimental method for creating underground storage cavities in clay deposits. Patents have been issued for the process, and approval to develop further the technique has been obtained from the patent holders (Ref. 18). The power required for rock or soil disintegration is developed primarily through chemical reactions. Details of the patented process are included in Appendix I.

This method consists of penetrating the selected formation with a drilled shaft through which is circulated from top to bottom an aqueous solution containing a deflocculant chemical. The deflocculant chemical deionizes the adsorbed bound soil water to release the soil particles and permit their erosion by downward flow. This deaggregation of the soil deposit results in a clay-laden solution. Withdrawal of the solution from the bottom and discharge into a desedimentation sump at the surface permits deposition of the soil solids and recirculation of the solution. The shape of the cavity is controllable to some degree by the technique used in introducing the deflocculant solution.

Theoretically, this method appears to be a relatively simple operation in which the key item is determination of the correct deflocculant chemical.

It was previously believed that certain laboratory tests such as mineralogy, X-ray diffraction, reaction to flocculants and deflocculants, cohesion permeability, chemical analysis, and cation exchange capacity would be performed on a soil sample, and the results could be used to determine the chemical or chemicals which would most effectively deaggregate the particular soil. It was anticipated that these data would be used to develop a table of soil characteristics versus effective chemical deflocculants. Thus, the results obtained from a few basic laboratory tests performed on soil samples from a proposed cavity zone would be correlated to the table in order to determine the required deflocculant chemical.

The problems involved in introducing the chemical deflocculant and withdrawing the clay-laden solution would be mechanical in nature and could be solved. Investigation of the mechanical aspects of the deaggregant method was initiated concurrently with chemical deflocculant studies.

The first step in investigation of possible chemical deflocculants was discussion of the problem in conferences and/or correspondence with specialists in various technical fields such as geology-mineralogy (Dr. R.E. Grim, Urbana, Illinois), soil physics (Dr. J.R. Runkles, College Station, Texas), and soil mineralogy (Dr. G. W. Kunze, College Station, Texas). It was tentatively concluded from these discussions that the most effective deflocculant agent would be commercially available calgon (sodium hexametaphosphate). Laboratory experiments were started to determine the deaggregant effect of varying concentrations of calgon on selected soil samples. Very slow disintegration of the soil occurred and the resultant conclusion was that calgon would not be effective time-wise in deaggregating clay soil.

The next step was to determine if some form of mechanical agitation would improve the efficiency of calgon as a deaggregating agent. The probe of a sonifier (high-frequency vibrator) was operated at varying distances from soil samples immersed in water or a calgon-water solution. With the probe operating at a frequency range of 20,000 to 30,000 cycles per second, the soil structure was destroyed and the clay was deaggregated for a distance of approximately 1/8 inch whenever the probe tip was immediately adjacent the sample. There was no apparent difference in soil deaggregation between samples in water or the calgon solution. As the probe was moved away from the sample the only visible result was creation of turbulence in the liquid. It is apparent that the high energy input resulted in very little soil deaggregation. Another laboratory experiment was conducted to determine the effects of agitation. A cylindrical cavity was carved into a five-inch diameter soil core. The core was then split lengthwise and the cut face was sealed to a glass plate. This permitted observation of agitation within the cavity. A calgon-water solution was introduced into the cavity and a small bladed rotary mechanical mixer was rotated within the cavity. Turbulence was created in the solution, but had very little deaggregation effect on the cavity walls.

The next step was laboratory experimentation with an array of chemicals in an effort to determine which could be used for deaggregation of soils. Procedures and results are documented in "Report of Acid Consumption of Clay Soils," which is included in Appendix II of this technical report. These experiments indicated that of all chemicals tried, acids were the only effective soil deaggregating reagents. Additional quantitative experiments showed a wide variation in acid consumption from soil sample to soil sample. Hydrochloric, nitric, sulfuric, and monochloroacetic acid were all

effective in destroying the clay soil structure. Cost data are included in the noted report. The use of acids as deflocculating agents would be both expensive and hazardous. In addition, corrosive effects and disposal problems would exist.

Based upon our laboratory experiments, research, conferences, and correspondence with technical specialists, it is concluded that the chemical deaggregant method of storage cavity creation is possible but not practical for general field application.

## 2. HYDRAULIC TECHNIQUE

Of all the methods of rock or soil excavation described by Maurer, hydraulic erosion appears to offer the best approach to achieving the ideal, i.e., low specific energies, high average energy delivery rates, low thrust requirements, high heat removal capabilities, convenient muck removal and low maintenance.

Experimental studies of this process were conducted by the Oak Ridge National Laboratory for the Department of Housing and Urban Development (Ref. 19, 20). The tests were designed to measure the specific energy of water jets under the following variable conditions:

- 1) Rock types ranging from sandstone to granite
- 2) Water pressures from a few thousand psi to 12,000 psi
- 3) Jet Nozzle sizes from 2 mm to 6 mm ID
- 4) Rates of movement of the jet in relation to the rock from about 30 to 90 cm/sec
- 5) Rock orientation, with the water jet striking the surface either perpendicular to or parallel to the bedding plane in the case of sandstone and limestone, and plane of foliation in the case of granite
- 6) Distance from nozzle front to rock surface (0.44 in. to 3.38 in.)

The results of these tests are shown in Figures 4, 5, 6, and Table III.

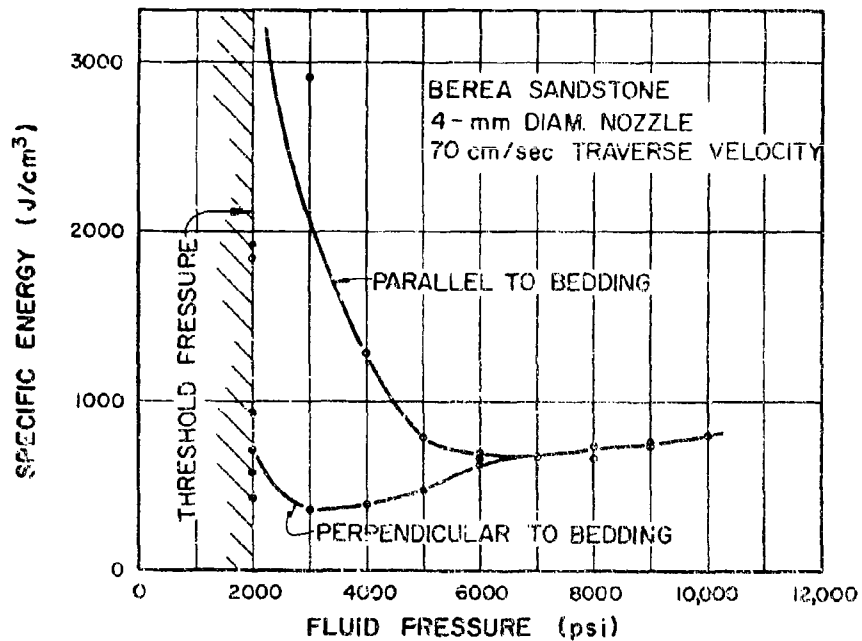


FIGURE 4. SANDSTONE TESTS SHOWED EXISTENCE OF A THRESHOLD PRESSURE BELOW WHICH NO CUTTING WAS DONE. THE EFFECT OF ROCK ORIENTATION AND THE HIGH-PRESSURE CONVERGENCE POINT ARE ALSO SHOWN ON CHART. STAND-OFF DISTANCE WAS 1.75 IN.

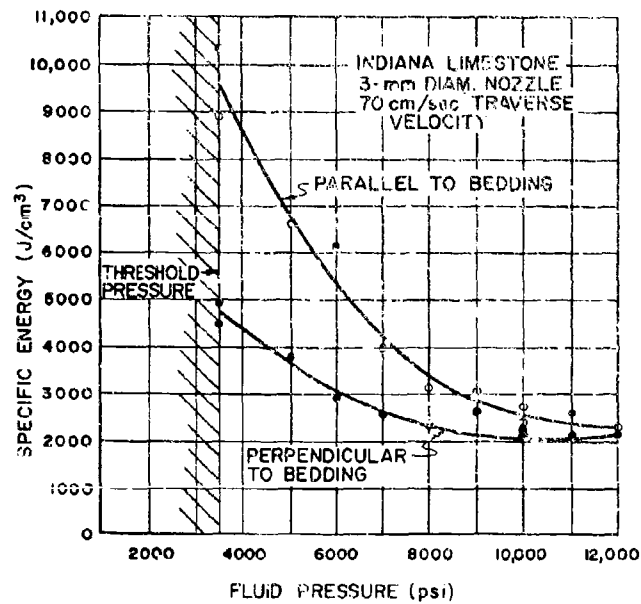


FIGURE 5. EFFECT OF WATER PRESSURE ON THE SPECIFIC ENERGY FOR INDIANA LIMESTONE SAMPLE. STAND-OFF DISTANCE OF JET WAS ALSO 1.75 IN. ATTACK AND CANT ANGLES WERE ZERO.



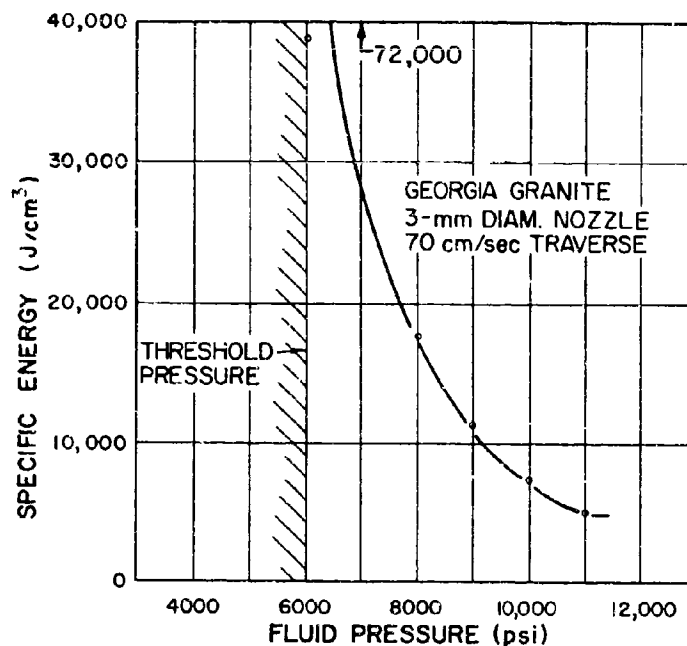


FIGURE 6. SPECIFIC ENERGY TESTS ON GEORGIA GRANITE SHOWED A THRESHOLD PRESSURE OF 6,000 psi. STAND-OFF DISTANCE ATTACK AND CANT ANGLES WERE AS IN FIGURES 4 AND 5.

TABLE III

SUMMARY OF MINIMUM SPECIFIC ENERGIES FOR EXPERIMENTAL CUTS

Type Rock	Jet Size (mm)	Fluid Pressure (psi)	Specific Energy (J/cm <sup>3</sup> )
SINGLE CUTS			
Berea Sandstone	2	6,000	650-800
	4	6,000	550-700
	6	6,000	500-700
Indiana Limestone	3	10,000	2,000-2,500
Georgia Granite	3	10,000	5,000-6,000
KERFING CUTS			
Berea Sandstone	2	6,000	350-550
	4	6,000	250-350
	6	6,000	350
Indiana Limestone	3	10,000	1,500-2,500
Georgia Granite	3	10,000	(400)*

(\* Jet oriented perpendicular to foliation only. No kerfing in other direction.)

Exotech Incorporated (Ref. 21), is conducting company-funded research to obtain data on the optimum water jet pressure and pulse energy desired for fracturing various rocks and minerals. They have successfully developed pulsed water jets at pressures of 100,000 psi and jets of liquid at pressures of 200,000 to over 5 million psi.

They report the most significant factors affecting rock disintegration are the jet stagnation pressure relative to the rock strength and the total kinetic energy of the water at the face of the rock. This is shown in Figure 7. The results show that as the jet pressure is raised to at least a factor of 10 higher than the rock compression strength, the energy required to fracture a given volume is decreased dramatically. In general the volume of the rock broken is proportional to the kinetic energy in the pulse raised to a power slightly greater than one. Tests have shown that further reductions of energy are possible by directing the jet near a free edge of rock in order to split off the largest fragments possible.

The sole purpose of increasing the jet velocity is to increase the jet stagnation pressure (the pressure exerted on the face as the water jet impacts). The water exerts a pressure given by the formula:

$$P = \frac{1}{2} \frac{\rho' V^2}{g} K$$

Where

P = Stagnation pressure, psi

$\rho'$  = Jet Density, lb/ft<sup>3</sup>

V = Jet Velocity, ft/sec

K = Liquid Compressibility Factor

g = 32.2 ft/sec<sup>2</sup>

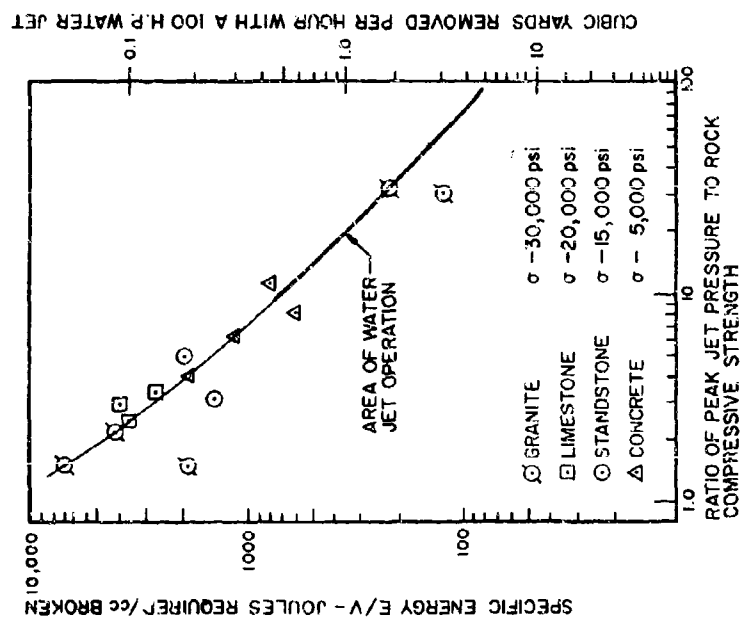


FIGURE 7. THE EFFECT ON VOLUME OF ROCK REMOVED BY RAISING THE JET IMPACT PRESSURE

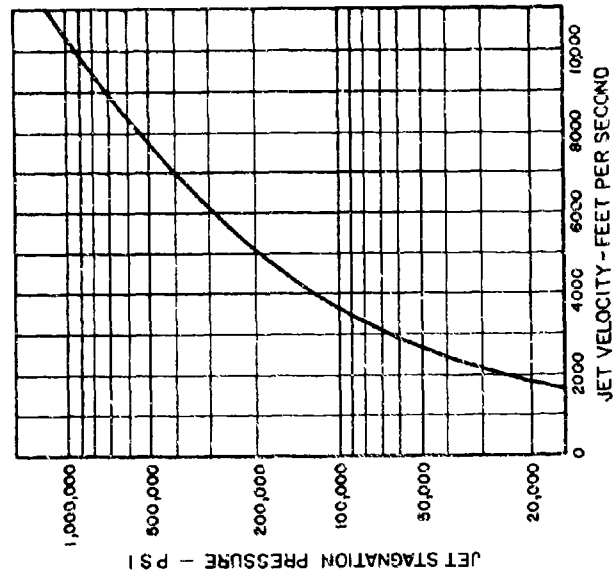


FIGURE 8. THE RELATIONSHIP BETWEEN WATER JET VELOCITY AND THE RESULTING STAGNATION PRESSURE

Figure 8 shows the relationship between the jet velocity and the stagnation pressure for water jets traveling up to 10,000 ft/sec.

A further advantage lies in the unique ability of a nozzle to deliver great amounts of energy to a rock surface without a correspondingly large back force. The equation for the power delivery of a jet at high pressure is:

$$P' = 3.486 (10^{-3}) A (p'')^{1.5}$$

Where

$P'$  = Output Horsepower, hp

$A$  = Nozzle Cross Sectional Area, sq cm

$p''$  = Water Pressure, psi

To illustrate, consider a 6 mm nozzle through which water is delivered at 10,000 psi; the output power is 1,000 hp. The flow rate through the nozzle would be 170 gpm. However, the back thrust from a single nozzle is simply the reaction force, i.e., the pressure multiplied by the cross sectional area. Thus,

$$F = p''A = 440 \text{ lb}$$

A successful method for hydraulic creation of subsurface cavities through small diameter bore holes has been developed by A. B. Fly of Hydro-Jet Services, Incorporated, Amarillo, Texas. Dowell Division of The Dow Chemical Company, Tulsa, Oklahoma, is currently developing a somewhat different technique for underground hydraulic mining. Details of both procedures are discussed in the following subsections.

a. A. B. FLY HYDRO-JET METHOD

A. B. Fly of Hydro-Jet Services, Incorporated, Amarillo, Texas, originally developed this process to increase production in water and oil wells by exposing greater area of the producing formation (Ref. 22). Application of the method was expanded to include hydraulic mining of subsurface materials. The equipment and techniques for excavating large cavities through small diameter boreholes are discussed in Appendix III.

Basically, borehole mining combines the principles of hydraulic mining, slurry mucking and rotary drilling. As illustrated in Figure 9, the borehole is drilled with conventional rotary type equipment and is cased to the top of the mining zone. A mining tool consisting of sidewall jet nozzles, a jet pump assembly, suction screen, and a tricone rock bit are suspended in the hole and connected to the surface and the pumps by multiple drill pipe sections and a kelly-swivel assembly. The kelly drive bushing engages the rotary table to allow rotation of the mining tool while it is being operated. Clean water is pumped at high pressure to the mining tool. A portion of the water is jetted out the side nozzles to cut the formation and wash the cuttings down to the rock bit. The remainder of the fluid issues to clean the bit, agitate the cuttings, and provide lift needed to pump the slurry to the surface through the jet pump. The jet pump may be augmented by an air-lift pump. Compressed air may be utilized for the air-lift pump to insure that the fluid level in the mined formation is below the sidewall jet stream. Details of the Hydro-Jet hydraulic underreamer are presented in Figure 10.

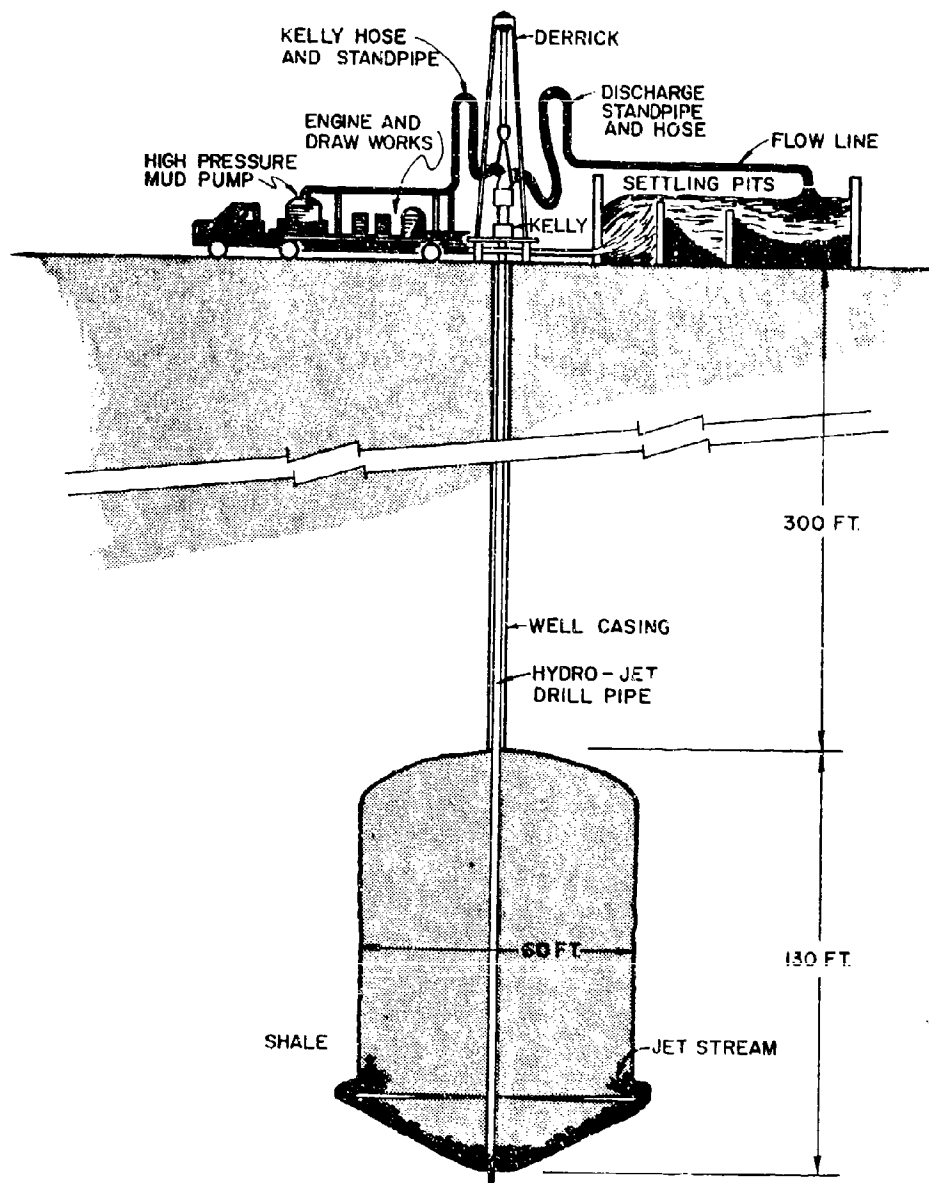


FIGURE 9. HYDRO-JET EQUIPMENT ILLUSTRATED IN POSITION UNDERREAMING A 50,000 BARREL UNDERGROUND STORAGE CAVERN.

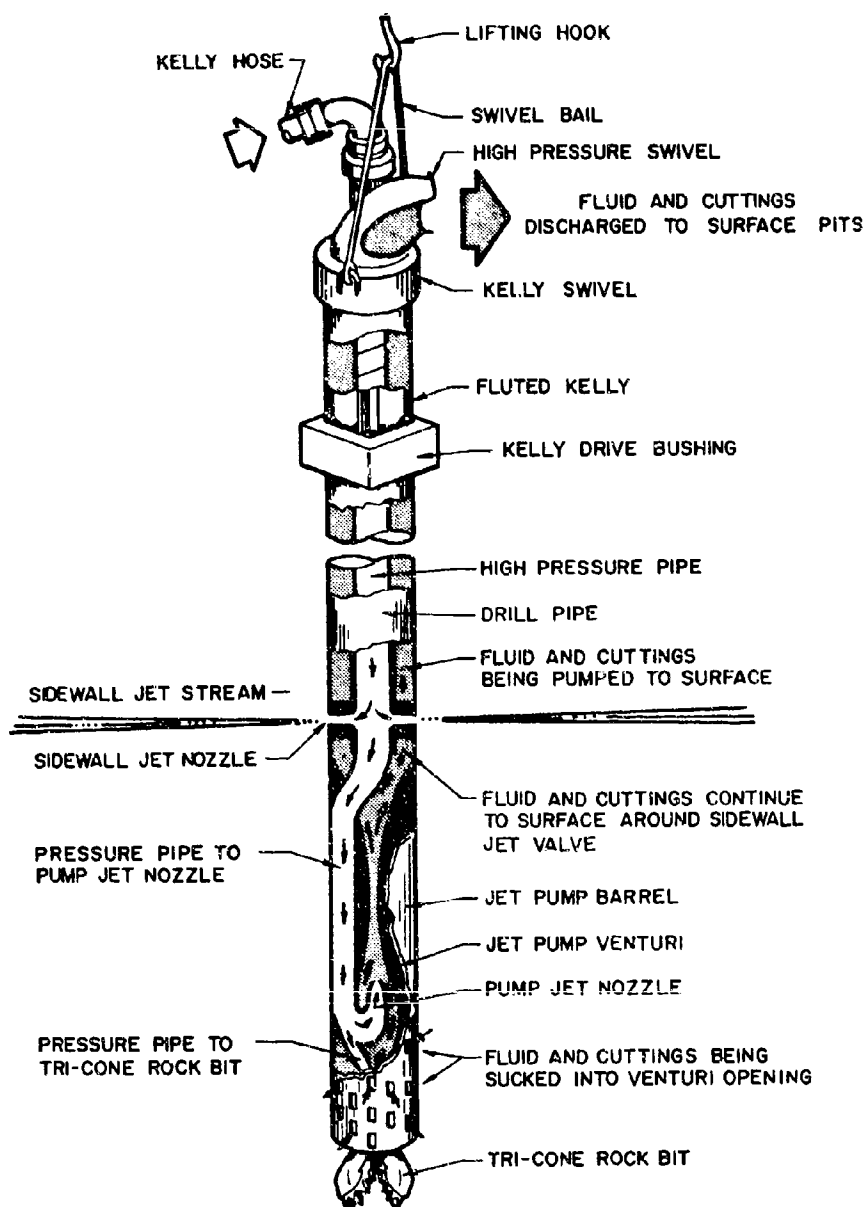


FIGURE 10. HYDRO - JET HYDRAULIC UNDER REAMER

Consolidated sandstones, weathered limestones and laminated shales have been successfully mined in operations to depths of 350 ft. Mining rates of one cubic yard per minute have been achieved and cavities have been excavated to a lateral distance of 30 feet from the borehole, or 60 feet in diameter.

The process has been used experimentally to mine bauxite in a formation 20 feet thick and some 225 feet beneath the surface near Bauxite, Arkansas. A representative of our firm observed the field test. Difficulties were encountered due to the strength and degree of cohesion of the bauxite. The fluid pressures available were not adequate to cut a part of the formation although success was achieved in softer areas. Cores of the rock formations were obtained and evaluated. Table IV compares the mechanical properties (obtained from tests performed in our laboratory), pressures and volumes of water utilized in the field tests, nozzle sizes, and results obtained.

Although experimentation with this method has been directed primarily toward excavation of rock type formations, it is evident that the technique would be successful in rapid creation of cavities in clay. However, it is likely that the existing equipment would require certain modifications in order to be applicable to cavity creation in clay soil.

Mr. Fly is currently experimenting with a modified method for creating underground cavities through small diameter bore holes. Steel shot are used in conjunction with high-pressure water jetting. The 3/8-inch diameter shot are ejected through a separate nozzle at 1200 feet per second at the rate of 6000 shot per minute. Compressed air (175-600 cfm) provides the ejection force. The energy per shot is 173 foot-pounds. The shot are recovered and recycled. Additional details are included in Appendix III. The



TABLE IV

TABLE II.

SUMMARY OF LABORATORY AND FIELD HYDRO-JET TEST DATA

APPROX. DEPTH (FT.)	LITH. SAMPLE NO.	TYPE OF MATERIAL	NATURAL MO. (%)	MOISTURE CONTENT, % SATUR.	DENSITY (pcf)	LABORATORY TEST DATA				PERMEABILITY (D)	HYDRAULIC SIZE (mm)	FIELD MEASURED PER MEASURE (gpm)	REMARKS	
						UNSATURATED COMPRESSION (psi)	SWELL (%)	TYPE FAILURE	SPECIFIC GRAVITY					
22.0	1	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	2	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	3	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	4	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	5	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	6	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	7	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	8	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	9	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	10	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	11	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	12	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	13	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	14	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	15	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	16	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	17	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	18	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	19	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	20	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	21	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	22	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	23	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	24	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	25	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	26	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	27	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	28	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	29	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	30	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	31	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	32	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	33	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	34	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	35	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	36	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	37	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	38	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	39	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	40	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	41	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	42	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	43	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	44	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	45	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	46	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	47	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	48	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	49	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	50	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	51	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	52	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	53	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	54	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	55	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	56	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	57	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	58	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	59	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	60	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	61	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	62	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	63	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	64	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	65	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	66	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	67	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	68	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	69	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	70	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	71	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	72	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	73	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	74	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	75	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	76	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	77	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	78	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	79	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	80	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	81	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	82	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	83	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	84	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	85	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	86	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	87	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	88	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	89	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	90	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	91	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	Gravelly, medium sandstone, with some pebbles in air. Max. cutting rate = 1/4 yd. per min. Did not attempt to cut.
22.0	92	Light Gray Sandstone	80	11	119	Saturated	1.2	S.	2.64	26.6	1/2	550-550	110-180	
22.0	93	Light Gray Sandstone												

technique has great potential for excavating subsurface formations.

b. DOWELL METHOD

Dowell Division of The Dow Chemical Company, Tulsa, Oklahoma, has developed the theory of a mining method for rapid extraction of minerals through a small diameter bore hole. Equipment is currently being readied for field tests.

They believe the most economical way of cutting material is by a hydraulic process and have designed and manufactured a wash tool which jets water under high pressure out of two nozzles located opposite to each other. The nozzles are so designed as to hold the water jet as tight as possible until it reaches the face or wall of the cavity thereby obtaining maximum use of the kinetic energy in the stream. It is planned to test the process in a shale formation 100-150 feet deep. Figures 11 and 12 illustrate the basic fundamentals of the system.

The system consists of a rotary drilling rig, a dual string of tubing inside a casing, and surface equipment to provide pumping of fluid. In its application, 10-3/4-inch surface pipe (casing) would be set to the top of the proposed cavity. The drilling string would be lowered into the surface pipe, water would be pumped through the annulus between the 7-inch casing and 3-1/2-inch tubing, and jetting started at the top of the desired cavity. The drill bit, located below the jetting tool, could grind up large formation lumps. The formation material, reduced in particle size by jetting and grinding, would be removed from the cavity by forced flow up through the bit and 3-1/2-inch tubing (reverse circulation). It may be necessary to utilize an air-pressure system to increase the efficiency of the operation.

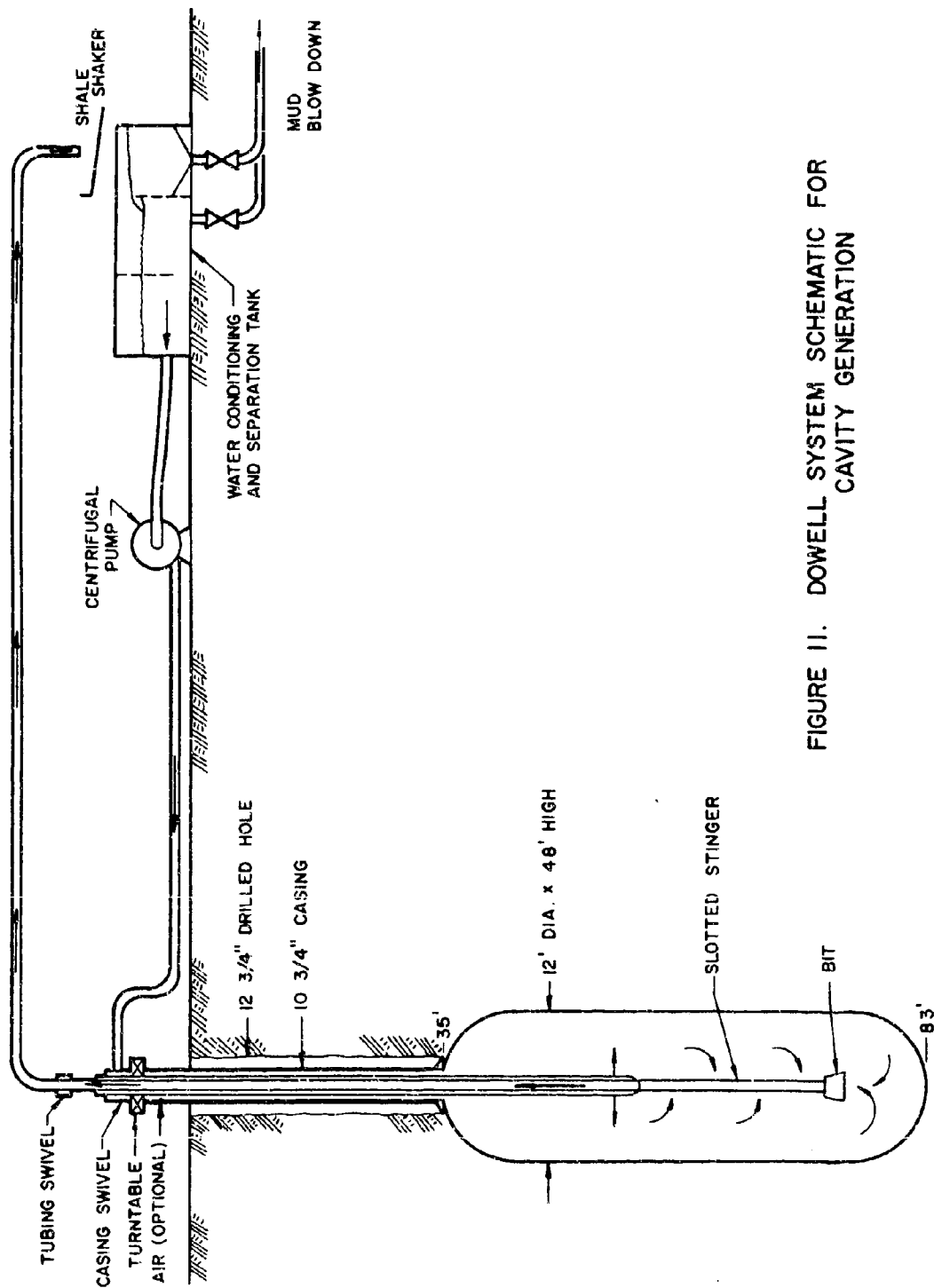
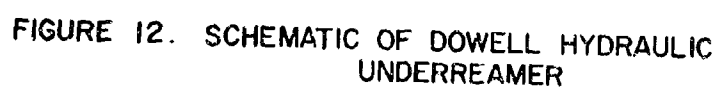


FIGURE 11. DOWELL SYSTEM SCHEMATIC FOR CAVITY GENERATION



Appendix IV contains a report prepared by Mr. W. M. Zings of Dowell Division of The Dow Chemical Company, Tulsa, Oklahoma. The report presents pertinent details of the proposed method. Although it has not yet been field tested, Dowell personnel are confident that the technique will be successful in creating a cavity in shale formations. If so, it can be assumed the procedure could be modified in order to successfully excavate subsurface cavities in clay soils.

## SECTION VI

### CAVITY CONFIGURATION

The ideal underground cavity configuration is one which is economical to create in any type material and is structurally stable regardless of the stress field or competency of the surrounding strata. Ideally, cavity configurations should be such that exact design formulas, based upon laboratory determined mechanical properties, are applicable. However, since the study of rock or soil mechanics is not an exact science, cavity configuration is determined by a combination of scientific, theoretical, and empirical methods.

Detailed explanations of the procedures for determination of cavity configurations are included in Appendix V. Among the factors which must be considered are the initial state of stress in the soil or rock mass, degree of lateral restraint, size of opening, elastic and inelastic properties of the rock or soil, and geologic discontinuities of the mass.

Figure 25 of Appendix V summarizes a range of selections for ideal cavity shapes in which the ratio of horizontal to vertical stresses ( $m = \frac{S_h}{S_v}$ ) varies. Table XI indicates the assumed in-situ ratio of horizontal to vertical stress for various soils.

As noted in Appendix V, the ideal cavity shape, as based upon structural integrity, may not be the most feasible or economical shape to create due to equipment limitations. If possible, configuration of cavities in various subsurface strata should approximate those indicated in Figure 25. It is not practical to predict the degree of control of the cavity shape. However, the hydraulic method has promise of reasonable control of cavity shape.

## SECTION VII

### STORAGE CAVITY INNERLINER

The storage of POJ. in an underground cavity necessitates the use of an innerliner (bladder) to function as a container inside the cavity in order to prevent contamination and/or loss of the stored product.

Desirable characteristics of the innerliner are:

- a. Capable of placement through small diameter bore hole.
- b. Resistant to volatile petroleum products, mechanical damage, weathering, and deterioration.
- c. Impermeable to water and petroleum products.
- d. Reasonably durable.
- e. Flexible over a wide range of temperatures.
- f. Low in cost.
- g. One piece.
- h. Resistant to subsurface microbiological attack.
- i. Alkali resistant.

Mr. John Hendershot (Ref. 23) has performed extensive research for determination of a desirable material to be placed inside deteriorated and leaking oil field steel storage tanks. He has developed a one-piece innerliner which is inserted inside the tank and serves as a container for the fluid.

Accelerated laboratory test programs, coordinated with field tests under actual precise conditions, have been performed with many types of rubber compounds, polyvinylchlorides and other materials. A series of laboratory tests has recently been completed by Dr. George W. Read, Civil Engineering Department, University of Oklahoma; however, a report of the

study has not been published. Also, the Product Division, Union Carbide Laboratory, Bound Brook, New Jersey, has evaluated several types of materials for Mr. Hendershot and Mobil Oil Company.

Numerous commercial field installations have confirmed all projections of the laboratory test results. It is reported that the best material found to date is UCB-030 (Ref. 23). This is an exotic thermoplastic polyvinylchloride sheeting manufactured by Union Carbide. It is easy to handle and reasonably tough, although the polymer that makes the material flexible loses a part of its effectiveness over a period of time and a decrease in elasticity, from about 350% to 225%, results.

TABLE V

UCB-030 LABORATORY TEST VALUES

Type Laboratory Test	Test Values
Tensile Strength	
Machine Direction	2332 psi
Transverse Direction	2061
Elongation	
Machine Direction	336 %
Transverse Direction	353
100% Modulus	
Machine Direction	995 psi
Transverse Direction	946
Graves Tear	
Machine Direction	307 lbs/inch
Transverse Direction	316
Low Temperature Impact	-12° F
Flammability, 45° SPI Test	Self Extinguishing

Liners are prefabricated to size, in one piece, by means of electronic welding process to assure positive leak-proof seams. They are packaged by folding accordin style in both directions. The fabricator is Fabrico,



Chicago, Illinois. For lowering through an opening, the liner is clamped to an adaptor ring by a fitting designed by Mr. Hendershot. This adaptor ring is attached to the end of a pipe. Thus, the liner in a collapsed condition can be lowered through a relatively small opening.

Originally, consideration was given to the possible use of a double innerliner system for the storage cavities. A positive air pressure would be introduced in the annulus between the two bladders. This regulated air pressure would be utilized to force the stored product from within the inner bladder. However, further study was abandoned as this system appeared to be more complicated than a system composed of a single innerliner with a pump for withdrawing the stored product.

After formation of the cavity and before insertion of the innerliner, a sand cushion approximately 2 feet thick should be installed in the bottom of the cavity. This should provide a relatively uniform bearing surface and reduce the possibility of bladder puncture from sharp objects on the cavity bottom.

Development of an innerliner specifically for use in underground storage cavities, constructed in accordance with the parameters established in this report, should require only minor modifications to existing techniques and materials currently used by Mr. Hendershot of Unit Liner Company, Wewoka, Oklahoma.

## SECTION VIII

### CAVITY WALL SEALANTS

An evaluation has been made of methods and chemicals which could possibly provide stability and impermeability to cavity walls. The petroleum industry has successfully used a number of additives to the fluid circulation system during drilling in order to reduce fluid loss in permeable strata. These various materials and methods are enumerated herein. Also included is a discussion of the possible use of embedment type polymer chemicals for cavity wall sealants.

The current rotary drilling technique was made possible by the development of the mud circulatory system. The history of the search for the "ideal" fluid is a story of compromise in that the formulations possessed characteristics of the "ideal," but also possessed undesirable offsetting characteristics (Ref. 24). Among the desirable properties of an "ideal" fluid system is the ability to reduce fluid loss in the hole to a minimum, but to do so with a minimum of solids deposition in the hole. A rather costly and time consuming formulation of separate systems for the various required applications evolved.

There are numerous chemicals and drilling fluid additives commercially available which have been used for sealing permeable strata and stabilization of certain soils. Among the major suppliers of these drilling muds are Baroid Division of National Lead Company, International Minerals and Chemical Corporation, Magcobar Division of Dresser Industries, and Milchem Incorporated. Standard ingredients in many drilling muds are gel-forming clay colloids obtained from processed bentonitic (montmorillonite) clay. To

reduce permeability of a particular porous stratum, this type of solids laden drilling mud is pumped into the hole and forms a relatively thin membrane on the face of the hole drilled through the formation. This quickly achieves minimum permeability and permits a small but fairly constant and continuous loss of fluid to the formation. In the event of highly permeable formation, fibrous materials may be added to the drilling mud.

"No-Solids" or polymer (chemical compounds or combinations formed by polymerization) type fluid systems are a fairly recent development in oil field technology. In this type system, either natural (organic) or synthetic polymers are applied in the preparation, maintenance, and use of drilling, workover, and completion fluids. Professor Bercegeay, Head of the Department of Petroleum Engineering at the University of Southwestern Louisiana, pioneered early work on the use of guar gum (a polysaccharide natural polymer) as an additive (Ref. 24). Also introduced was a number of colloidal systems utilizing various polymers such as hydrolyzed or otherwise modified polyacrylonitrils. When properly applied, the correct polymer system will completely plug off formation capillaries. One of the more serious problems confronting the petroleum industry is a lack of definitive, quantitative techniques for properly defining the properties of typical polymer solutions.

Petroleum Associates of Lafayette, Inc., Lafayette, Louisiana, has developed a number of polymer drilling fluid systems to be used for various purposes. They have determined that the reversion of organic systems, such as guar systems, by oxidation resulted in a solid precipitate in the well. They now market certain materials which can be added to the polymer drilling mud to permit it to revert to essentially water at a predetermined time.

Homogeneous clay soil strata are the ideal location for cavities created by the hydraulic technique; however, homogeneous clay strata are seldom located. Clay soils are often interbedded with sand layers of varying thickness. Sand normally is more pervious and has a lower cohesion than clay. It may be necessary to grout these layers of granular material so as to provide cavity wall stability. The technique for intentionally converting the viscous fluid system to a competent plastic and back to fluid, at will, may have some possible application to POL storage cavity wall sealing in granular materials.

Industrial grouting companies such as Halliburton have sealed storage cavity walls and chemically stabilized soils. However, all the foregoing applications have one item in common. They are used to seal permeable formations such as sand or fissured hard rock formations such as limestone. Normally, it is not necessary to seal clay type soil because of the very low in-situ permeability. The clays cannot be penetrated with enough polymer grout to adequately consolidate and seal the soil.

Consideration has been given to installation of a cement type grout wall, approximately 4 inches thick, between the innerliner and the cavity wall. This would provide structural stability to the cavity wall and preclude isolated wall failures whenever the stored product is withdrawn from the cavity. However, the practicability of this technique is questionable.

Jet fuels, gasolines, and other petroleum products have high quality requirements and are very susceptible to contamination. With materials such as polymer grouts or drilling muds, it would be virtually impossible to completely seal the interior walls of an underground cavity. It is therefore our conclusion that a cavity wall sealant, in lieu of innerliners, will not provide the high quality requirements in regards to contamination.

## SECTION IX

### CAVITY OPERATIONAL CONDITIONS

Operation of underground storage cavities should not be complex. Several methods are available for removal of POL products from subsurface cavities. A normal pumping system connected to a dispensing facility may be utilized for shallow cavities. For deeper installations, a surface mounted motor with submerged pump or a pump-air pressure system may be required.

It is likely that ground water will be encountered during both construction and operation of subsurface cavities. It is possible that water will seep between the innerliner and cavity wall and tend to cause the innerliner to float or collapse, thereby progressively reducing the storage capacity. Therefore, provision must be made to maintain the system devoid of ground water. This can be accomplished by the dry-well method whereby a vertical shaft and sump would be installed alongside the cavity wall. Water which enters the cavity would drain into the sump and be removed by some means such as a sump pump. An alternate technique would be utilization of a positive air pressure, at greater than hydrostatic pressure, inside the innerliner. This would force groundwater from between the cavity wall and innerliner. As previously noted, the air pressure would also assist in removal of the stored product.

Operational techniques have not been detailed in this report as they are not part of the project scope. During operational tests, methods should be evaluated for loading and unloading POL products and for removing infiltrated groundwater.

## SECTION X

### SOILS DATA IN DESIGNATED STORAGE AREAS

A study of available literature, well logs, and core data was made to ascertain the types of formations existing in designated storage areas, Viet Nam, Thailand, and Korea. Following are generalized geologic data and soil lithology information for the three designated storage areas:

#### 1. SOUTH VIET NAM

The Republic of Viet Nam is divided into five geomorphic provinces, defined essentially by similar terrain features. These are the Annam Mountains, Central Plateau, Southern Plains, Mekong Delta, and Coastal Lowlands. The provinces are underlain by one or more of six geologic formations (Ref. 25). Beach deposits of recent geologic age underlie about half of the Coastal Lowlands. Recent delta and flood plain alluviums are exposed over most of the Mekong Delta and some parts of the Coastal Lowlands. Recent stream channel alluviums are scattered in the Annam Mountains, the Central Plateau, and the Southern Plains. Ancient alluvium of Pleistocene age underlies about two-thirds of the Southern Plains. Basalt is exposed over about one-third of the Southern Plains and about one-half of the Central Plateau. Bedrock complex underlies most of the Annam Mountains, and the other half of the Central Plateau. Soil lithology is as varied as the terrain. Shallow formations range from hard deposits such as granite in the mountain ranges to highly plastic sedimentary clay in the delta. Included in the assortment of formations are sands, silts, gravels, laterites, basalts, etc.

## 2. THAILAND

Thailand is composed of a number of greatly varying shallow soil formations. Typically, the geology ranges from the alluvium type unconsolidated deposits such as sand and clay in the lowlands to hard rock such as granite in the mountains. A great portion of the highland area consists of shale, sandstone, and limestone.

## 3. KOREA

Although numerous potential informational sources were contacted, no definite soil lithology information was obtained. It can be assumed reasonably that the soils range from highly plastic clay to hard igneous metamorphic type rocks.

Obviously, it would be a monumental task to attempt to catalogue the locations of all the numerous soil and rock formations present in the three designated countries. The usefulness of such a detailed resume in this report is questionable, as it would be necessary to obtain detailed soil information in the immediate vicinity of any proposed underground storage facility before construction of same. It is also likely that considerable variation in soil formations may exist between different areas of the same installation.

The hydraulic method of cavity formation is not dependent upon the cation exchange capacity of the soil. However, the optimum cavity shape as well as the amount of pressure required for hydraulically cutting the cavity depend upon the type and consistency of material to be penetrated. It will be necessary therefore to obtain samples, and subsequently determine the engineering characteristics of the soil or rock from the proposed underground storage locations. Normal soil exploration and laboratory

testing procedures can be utilized for determining the required data. Analysis of this soils information will be used to determine the desired size and shape of cavity and the approximate pressure which must be developed in order to erode the cavity.



## SECTION XI

### CONCLUSIONS

The United States Air Force currently utilizes a variety of methods for storage of POL products. Surface storage containers, such as steel tanks and collapsible bladders, are susceptible to damage by conventional weapons. Construction of underground storage tanks, which are less susceptible to conventional weapons effects, is expensive and time consuming. As detailed in preceding sections of this report, the existing methods for underground cavity formation are generally not adaptable to Air Force field usage.

Research for this report indicates processes for subsurface cavity formation are presently in a very active state of applied research. New ideas are emerging rather frequently as a result of numerous potential applications. The creation of cavities by the experimental chemical deaggregant technique has been found in this study to be possible but not practical. However, it is both feasible and practical to provide protective POL product storage within an innerliner installed inside a hydraulically created underground cavity.

We did not consider it necessary to hydraulically create a cavity specifically for this feasibility report. The Dowell hydraulic method is feasible and currently is in the development stage; however, the A. B. Fly Hydro-Jet technique has been successfully used to remove soil and rock from subsurface strata, thereby creating a cavity. Our analysis of the literature, and our observations of field tests conducted concurrent with this study convince us that the A. B. Fly technique is applicable to

creating underground cavities in accordance with the parameters established in Section I of this report.

The desired shape of a cavity to provide maximum stability may be determined, and is dependent upon the type and characteristics of the soils and the in-situ pressures within the formations. An inert innerliner (bladder) of the desired size and shape can be fabricated by the Unit Liner Company for insertion into the cavity through the surface casing. The innerliner should rest upon a sand cushion. It will probably be necessary to install a system to dewater the cavity. It is likely that segments of the cavity walls may be strengthened, but not completely sealed, by application of a selected grout between the innerliner and cavity walls. Complete and thorough subsurface soils data should be secured for the immediate area where cavities are to be formed in theaters of operation.

## SECTION XII

### RECOMMENDATIONS

Since feasibility of the underground storage cavity method has been established, it is recommended that conceptual and operational tests be conducted. Test cavities should be constructed utilizing the hydraulic cavity creation technique. A proposed site for construction of the test cavities is in the vicinity of Bryan, Texas. As determined by soil borings, the geologic formation is cohesive clay and sandy clay of stiff to hard consistency. Logs of Borings and Summary of Laboratory Test Data are included in Appendix VI.

Two cavities should be designed for 1,000 barrel capacities each and one cavity for 5,000 barrel capacity. The desired cavity configuration for structural stability is ellipsoidal with height to width ratio of 4 to 1; however, restrictions of the available equipment will likely necessitate creation of an ovaloidal cavity of the desired dimensions. The 1,000 barrel cavity should have a diameter and height of 12 and 48 feet, respectively, while the 5,000 barrel cavity should have a diameter and height of 20.5 and 82 feet, respectively.

An innerliner such as that supplied by the Unit Liner Company should be installed within the cavity. Also, systems should be installed and evaluated for withdrawal of products stored within the cavity, and for withdrawal of ground water between the cavity wall and innerliner.

## APPENDIX I

### CHEMICAL DEAGGREGANT TECHNIQUE

This appendix presents a copy of United States Patent Number 2,803,432, "Method of Forming Underground Cavity" and United States Patent Number 2,983,103, "Underground Storage of Fluids in Clay Beds".

Aug. 20, 1957

C. F. TEICHMANN ET AL

2,803,432

METHOD OF FORMING UNDERGROUND CAVITY

Filed Aug. 23, 1952

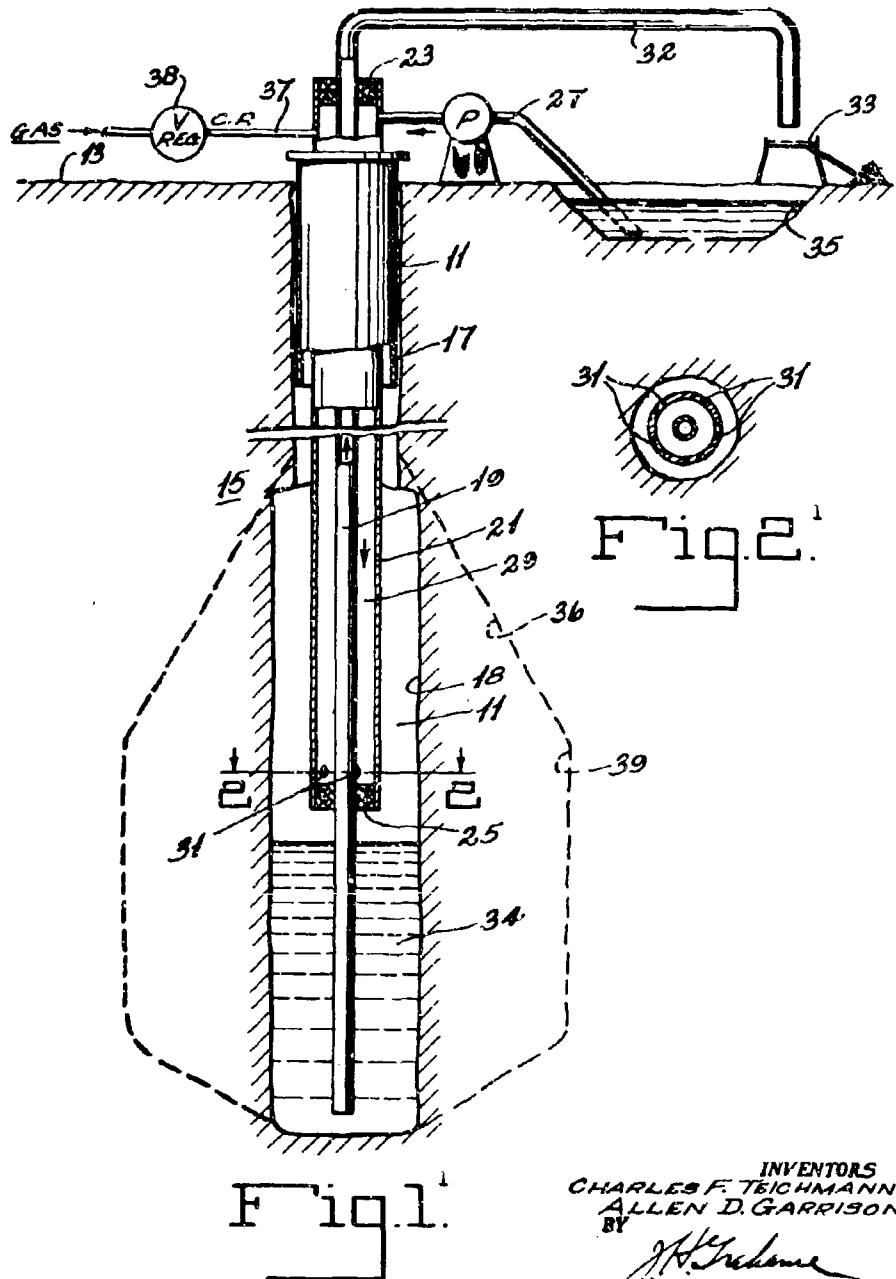


FIGURE 13. METHOD OF FORMING UNDERGROUND CAVITY

These figure numbers refer to Appendix I text.

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ATTORNEY

1

2,803,432

## METHOD OF FORMING UNDERGROUND CAVITY

Charles F. Teichmann, Crestwood, N. Y., and Allen D. Garrison, Houston, Tex., assignors to Texaco Development Corporation, New York, N. Y., a corporation of Delaware

Application August 23, 1952, Serial No. 345,964

5 Claims. (Cl. 255-1)

The present invention relates to the storage of fluids, such as liquefied petroleum gases, in underground storage cavities formed in clay beds beneath the surface of the earth.

Such fluids as liquefied petroleum gases have been stored successfully within tremendous cavities formed in salt formations hundreds of feet below the surface of the earth. Storage in salt cavities has proven quite successful but, unfortunately, underground salt formations suitable for this purpose are not available at every location where storage space is needed. It is well known that large underground clay formations are located in numerous places where no salt formations exist, but up to the present time there has been no known way for utilizing such clay formations to store fluids.

In accordance with the present invention we have found that a large underground storage cavity can be formed within a clay formation hundreds of feet below the surface of the earth by flowing into contact with such a clay body a deflocculant liquid which deflocculates the clay and forms a clay-laden liquid, which is then removed from the clay body to form a large cavity having a wall. While water alone is a liquid which has some deflocculating effect upon clay, we prefer to employ a water solution of one or more chemicals which have a more pronounced deflocculating effect, for example, the molecularly dehydrated phosphates.

After the cavity has been enlarged sufficiently it is advantageous to treat its walls to reduce their permeability, and to prevent further deflocculation during operation for storage purposes. Permeability can be decreased by treating the walls of the cavity with a material such as sodium silicate in water solution. While the sodium silicate can be employed alone in water solution, it is advantageous to react the deposited sodium silicate with a material which causes silicic acid or silica to precipitate from the sodium silicate solution and deposit within the pores of the clay wall. Another procedure for reducing permeability is to coat the walls with a polymerized plastic material such as rubber.

Continued deflocculation of the clay walls of the cavity can be avoided after its completion by treating the walls with a water solution containing a flocculating agent, such as one or more salts from the group consisting of sodium and potassium thiocyanates, chlorates, iodides, nitrates, bromides, chromates, and chlorides. These agents can be employed in a separate solution or in the sodium silicate solution previously mentioned.

In the drawing:

Fig. 1 is a schematic vertical sectional view of novel apparatus for creating a storage cavity in a bed of clay by the principles of the invention; and

Fig. 2 is a cross-sectional view taken along the line 2-2 in Fig. 1.

More in detail in accordance with the invention, the first step after locating an underground clay bed of sufficient thickness is to drill a deep hole 11 from the surface of the earth 13 down through intervening overburden

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into the clay formation 15. The top portion of the hole 11 preferably is cased at 17 to prevent the caving of overburden as the hole progresses. The bottom portion of the hole desirably is under-reamed to increase its diameter, as at 18, thus expediting formation of the final cavity.

After completion of the hole 11 a long central pipe 19 terminating in an entrance is inserted to a point such that its entrance is a few inches from the bottom of the hole for the removal of clay-laden liquid to the surface 13.

Surrounding the central pipe 19 in spaced relation thereto is a second pipe 21 which also extends down from the surface 13 into the hole 11, but terminates a substantial distance above the bottom of the central pipe 19 for the injection of deflocculant liquid into the hole. Packing glands 23 and 25 are disposed in the annulus 29 between pipes 19 and 21 to prevent leakage of liquid while permitting the outside pipe 21 to be moved lengthwise along the central pipe 19 to enlarge the hole along its full length.

Deflocculant liquid is pumped through a conduit 27 and injected down through the annulus 29 between the two pipes and is then discharged into the hole 11 through a plurality of circumferentially spaced discharge ports 31 above the gland 25. The washing action of the deflocculant liquid is enhanced by discharging it through the ports 31 as a plurality of lateral streams or jets with such a high velocity that they impinge against the side walls of the hole and wash the deflocculated clay detritus down to the bottom where the clay-laden liquid 34 enters the central pipe 19 and is raised to the surface of the earth there to be discharged through a pipe 32 into a screen 33 which removes much of the clay, and thence into a slush pit 35 in which the remaining clay settles. The washing action is accentuated by so constructing the ports 31 that they extend generally tangentially at an angle to the pipe radius, as in Fig. 2, and thus discharge the liquid jets non radially so that they swirl around the wall of the hole.

Pipe 21 can be translated lengthwise of the hole to move the injected streams lengthwise and extend the hole diameter the full length of the desired cavity while maintaining the lower end of pipe 19 near the bottom of the hole. Preferably the movement at the top should be such as to form a conical ceiling 36 on the final cavity 39 to prevent caving of the ceiling.

While water alone has some deflocculating effect on clay, it is preferred to incorporate in the water one or more chemical compounds which increase the deflocculating effect and thus increase the speed of operation. Among such chemical compounds are the alkali and alkaline earth metal polyphosphates, such as sodium or potassium tetraphosphate and triphosphate. The deflocculating effect is aided by such materials even when present in very small amounts, but the effect increases progressively as the amount increases up to saturation. A suitable deflocculant liquid may contain between .001 and 0.50 percent of one or more of the above compounds.

The clay-laden deflocculant liquid 34 can be removed through the central pipe 19 in any desired way, as by employing a suction pump or by operation with the cavity full of liquid under a hydrostatic pressure head. We prefer, however, to force the liquid up at a rate such as to maintain the level of the liquid pool in the hole at a point some distance below the ports 31 and the streams therefrom, but a substantial distance above the entrance of pipe 19, by maintaining a layer of gas under pressure above the liquid, thus making it possible for the high velocity jets from ports 31 to flow through gas filled space and impinge directly against the side walls of the hole and exert the maximum washing effect. Any suitable gas such as natural gas, air, or carbon dioxide, can be employed,

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37 into the annulus 29 to flow down into the hole along with the deflocculant liquid. A conventional pressure regulator 38 maintains a constant gas pressure in the hole.

Since the deflocculant liquid containing polyphosphates or other deflocculating chemicals is quite valuable, recirculation should be employed, as by pumping used liquid from the slush pit 35 back into the annulus 29. Make-up liquid can be added as needed.

It may be found in some clays that the deflocculant liquid acts so rapidly upon the clay wall of the hole that the proportion of deflocculated clay in the liquid pool 34 becomes too large to handle effectively. When such a situation arises it is desirable to retard deflocculation temporarily by injecting into the hole through the annulus 29 a water solution containing a flocculating material such as sodium or potassium chloride or the other materials mentioned previously herein to flow intermittently into contact with the clay body to retard the rate of clay removal from the cavity wall. After a short time the flow of deflocculating liquid can be resumed. This alternate action of deflocculating and flocculating liquids can be employed as often as necessary to maintain the steady progress of hole enlargement.

After the hole 11 has been enlarged to the desired diameter over the desired length to form a storage cavity 39, the clay walls of the cavity should be treated to assure impermeability, thus to prevent the leakage of liquefied petroleum gases or other liquids which are to be stored. This can be done by impregnating the wall of the hole with a sodium silicate solution to fill up the pores. For example, a water solution containing 10 to 20 percent by volume of a low alkali sodium silicate in which the molecular ratio of silica to sodium oxide falls within the range of from 3.9:1 to 1.5:1 can be introduced into the storage cavity to fill the latter, or can be applied to the walls by spraying it from the ports 31. If the sodium silicate treatment alone is not completely satisfactory, it can be followed by treatment with a solution of a multivalent salt such as calcium or aluminum chloride or a dilute acid solution such as dilute sodium chloride or hydrochloric acid, to precipitate silicic acid or silica.

Another procedure which can be used successfully is to spray such a sodium silicate solution on the walls of the storage cavity through ports 31 while maintaining within the storage cavity a large volume of a gas containing a sufficient quantity of carbon dioxide to react with the deposited sodium silicate and precipitate silicic acid. Such a gas can be introduced from conduit 37 before or after the silicate solution.

Not only should the walls of the storage cavity be rendered as impermeable as possible, but there must also be assurance that further deflocculation will not occur when the cavity is later operated for the storage of fluids. This can be accomplished by applying to the walls of the storage cavity 39 a solution of a flocculating chemical compound such as sodium or potassium chlorides, or any other salt selected from the group consisting of the sodium and potassium thiocyanates, chlorates, iodides, nitrates, bromides, chromates, and chlorides. While even minor quantities of these salts inhibit deflocculation, it is desirable to maintain the salt content of the solution within the range of from 20 percent by weight up to the saturation value of the dissolved component. The salt can be applied as a separate solution or can be incorporated in the sodium silicate solution previously mentioned.

After the storage cavity 39 has been completed as described above, it can be immediately used for the storage of a fluid such as liquefied petroleum gas. The cavity can be filled with a suitable control liquid such as a water solution and the liquefied petroleum gas then pumped down through the annulus 29 to displace solution up through the central pipe 19. When gas later is to be withdrawn from the storage cavity, solution is pumped down through the central pipe 19 and displaces gas up

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through the annulus 29. In order to maintain the walls of the storage cavity in a compact and impermeable condition it is advantageous to use as the control liquid a water solution of sodium silicate with or without a flocculant salt of the type described previously herein.

Obviously, many modifications and variations of the invention, as hereinbefore set forth, may be made without departing from the spirit and scope thereof, and therefore only such limitations should be imposed as are indicated in the appended claims.

We claim:

1. A method for extracting clay from an underground clay body and forming an underground storage cavity therein, said method comprising flowing into contact with said clay body a water solution of a deflocculant chemical, thereby deflocculating clay with said solution and forming clay-laden liquid; removing said clay-laden liquid from said clay body, thereby forming a cavity having a wall; depositing sodium silicate solution on said wall; and introducing carbon dioxide gas into said cavity to react with said sodium silicate and deposit a precipitate on said wall to reduce permeability thereof.

2. A method for extracting clay from an underground clay body and forming an underground cavity therein, said method comprising flowing into contact with said clay body a water solution of a deflocculant chemical; deflocculating clay with said solution and forming clay-laden liquid; removing said clay-laden liquid from said clay body, thereby forming a cavity having a wall; intermittently flowing into contact with said clay body a flocculant liquid to retard the rate of clay removal from said wall; and then resuming the flow of said water solution of a deflocculant chemical.

3. A method for extracting material from an underground earth formation and forming an underground cavity therein, said method comprising drilling a hole from the surface of the ground down into said formation; inserting a pair of spaced pipes into said hole and extending down into said formation, one pipe extending below the other pipe and terminating in an entrance near the bottom of said hole; injecting a material-removing liquid through said other pipe and thence through gas filled space against the wall of said hole in a plurality of high velocity lateral streams to wash removed material down from said wall and form a pool of material-laden liquid; maintaining the level of said pool below said streams, but a substantial distance above said entrance, by maintaining a layer of gas under super atmospheric pressure above said pool; and forcing material-laden liquid from said hole through said one pipe by the pressure of said gas at a rate such that the level of said pool is maintained below said lateral streams.

4. A method in accordance with claim 3 wherein said lateral streams are injected non-radially and swirl around said wall.

5. A method in accordance with claim 3, also comprising moving said streams lengthwise of said hole by translating said other pipe lengthwise to increase the size of said cavity while maintaining the lower end of said one pipe near the bottom of said hole.

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May 9, 1961

C. F. TEICHMANN ET AL

2,983,103

UNDERGROUND STORAGE OF FLUIDS IN CLAY BEDS

Filed Jan. 17, 1957

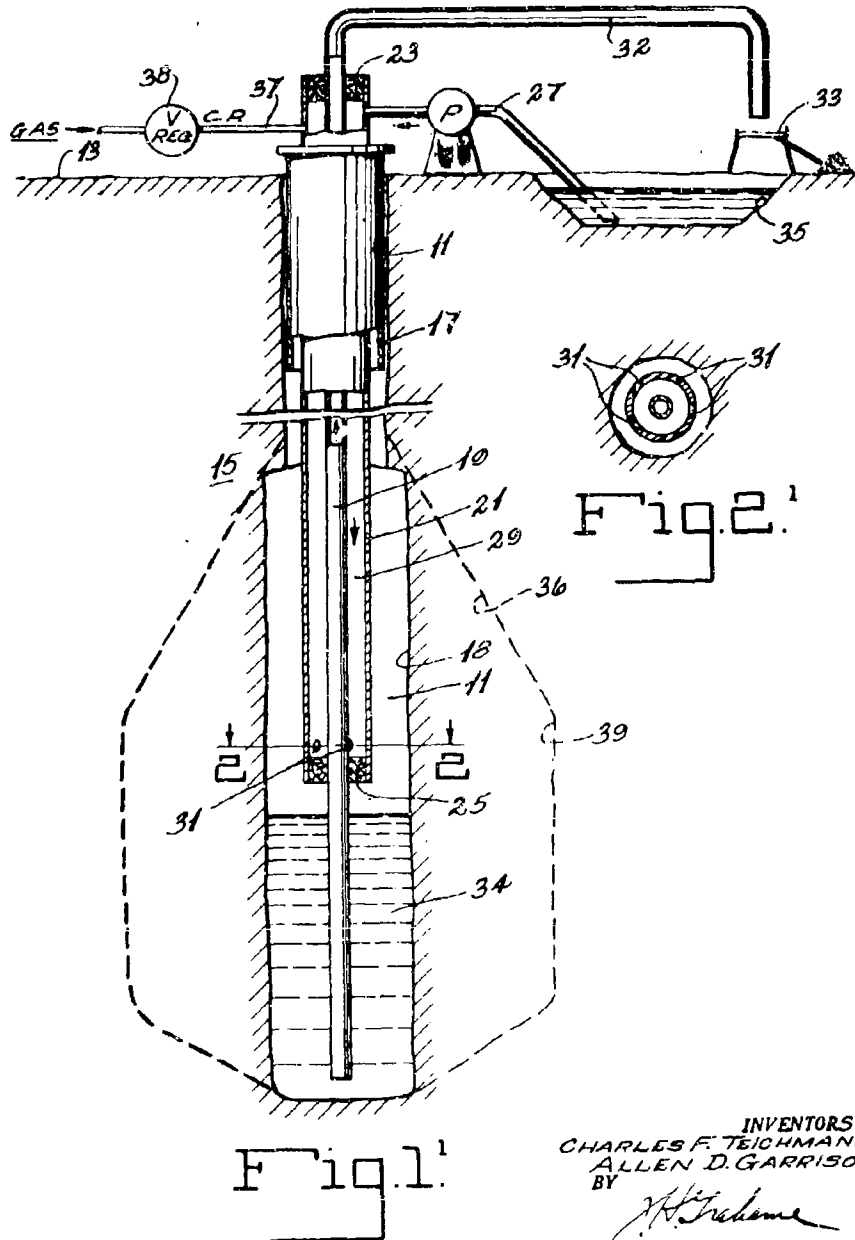


FIGURE 14. UNDERGROUND STORAGE OF FLUIDS IN CLAY BEDS

<sup>1</sup>These figure numbers refer to Appendix I text.

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2,983,103

## UNDERGROUND STORAGE OF FLUIDS IN CLAY BEDS

Charles F. Teichmann, Crestwood, N.Y., and Allen D. Garrison, La Jolla, Calif., assignors to Texaco Development Corporation, New York, N.Y., a corporation of Delaware

Filed Jan. 17, 1957, Ser. No. 634,687

1 Claim. (Cl. 61—5)

The present invention relates to the storage of fluids, such as liquefied petroleum gases, in underground storage cavities formed in clay beds beneath the surface of the earth.

Such fluids as liquefied petroleum gases have been stored successfully within tremendous cavities formed in salt formations hundreds of feet below the surface of the earth. Storage in salt cavities has proven quite successful but, unfortunately, underground salt formations suitable for this purpose are not available at every location where storage space is needed. It is well known that large underground clay formations are located in numerous places where no salt formations exist, but up to the present time there has been no known way for utilizing such clay formations to store fluids.

In accordance with the present invention we have found that a large underground storage cavity can be formed at the bottom of a well within a clay formation hundreds of feet below the surface of the earth by flowing into contact with such a clay body a deflocculant liquid which deflocculates the clay and forms a clay-laden liquid, which is then removed from the clay body to form a large cavity. While water alone is a material removing liquid which has some deflocculating effect upon clay, we prefer to employ a water solution of one or more chemicals which have a more pronounced deflocculating effect, for example, the molecularly dehydrated phosphates.

After the cavity has been enlarged sufficiently it is advantageous to treat its walls to reduce their permeability, and to prevent further deflocculation during operation for storage purposes. Permeability can be decreased by treating the walls of the cavity with a material such as sodium silicate in water solution. While the sodium silicate can be employed alone in water solution, it is advantageous to react the deposited sodium silicate with a material which causes silicic acid or silica to precipitate from the sodium silicate solution within the pores of the clay wall. Another procedure for reducing permeability is to coat the walls with a polymerized plastic material such as rubber.

Continued deflocculation of the clay walls of the cavity can be avoided after its completion by treating the walls with a water solution containing a flocculating agent, such as one or more salts from the group consisting of sodium and potassium thiocyanates, chlorates, iodides, nitrates, bromides, chromates, and chlorides. These agents can be employed in a separate solution or in the sodium silicate solution previously mentioned.

In the drawing:

Fig. 1 is a schematic vertical sectional view of novel apparatus for creating a storage cavity in a bed of clay by the principles of the invention; and

Fig. 2 is a cross-sectional view taken along the line 2—2 in Fig. 1.

More in detail in accordance with the invention, the first step after locating an underground clay bed of sufficient thickness is to drill a deep hole or well 11 from the surface of the earth 13 down through intervening

2

overburden into the clay formation 15. The top portion of the hole 11 preferably is cased at 17 to prevent the caving of overburden as the hole progresses. The bottom portion of the hole desirably is under-reamed to increase its diameter, as at 18, thus expediting formation of the final cavity.

After completion of the hole 11 a long central pipe 19 is inserted to a point a few inches from the bottom of the hole for the removal of clay-laden liquid to the surface 13.

Surrounding the central pipe 19 in spaced relation thereto is a second pipe 21 which also extends down from the surface 13 into the hole 11, but terminates a substantial distance above the bottom of the central pipe 19 for the injection of deflocculant liquid into the hole. Packing glands 23 and 25 are disposed in the annulus 29 between pipes 19 and 21 to prevent leakage of liquid while permitting the outside pipe 21 to be moved lengthwise along the central pipe 19 to enlarge the hole along its full length.

Deflocculant liquid is pumped through a conduit 27 down through the annulus 29 between the two pipes and is then discharged into the hole 11 through a plurality of circumferentially spaced discharge ports 31 above the gland 25. The washing action of the deflocculant liquid is enhanced by discharging it through the ports 31 as jets with such a high velocity that they impinge against the side walls of the hole and wash the deflocculated clay detritus down to the bottom where the clay-laden liquid 34 enters the central pipe 19 and is raised to the surface of the earth there to be discharged through a pipe 32 into a screen 33 which removes much of the clay, and thence into a slush pit 35 in which the remaining clay settles. The washing action is accentuated by so constructing the ports 31 that they extend generally tangentially at an angle to the pipe radius, as in Fig. 2, and thus discharge the liquid jets so that they swirl around the wall of the hole.

Pipe 21 can be moved lengthwise of the hole to extend the hole diameter the full length of the desired cavity. Preferably the movement at the top should be such as to form a conical ceiling 36 on the final cavity 39 to prevent caving of the ceiling.

While water alone has some deflocculating effect on clay, it is preferred to incorporate in the water one or more chemical compounds which increase the deflocculating effect and thus increase the speed of operation. Among such chemical compounds are the alkali and alkaline earth metal polyphosphates, such as sodium or potassium tetraphosphate and triphosphate. The deflocculating effect is aided by such materials even when present in very small amounts, but the effect increases progressively as the amount increases up to an optimum. A suitable deflocculant liquid may contain between .001 and 0.50 percent of one or more of the above compounds.

The clay-laden deflocculant liquid 34 can be removed through the central pipe 19 in any desired way, as by employing a suction pump or by operation with the cavity full of liquid under a hydrostatic pressure head. We prefer, however, to maintain the level of the liquid in the hole at a point some distance below the ports 31 by maintaining a gas under pressure above the liquid, thus making it possible for the high velocity jets from ports 31 to impinge directly against the side walls of the hole and exert the maximum washing effect. Any suitable gas such as natural gas, air, or carbon dioxide, can be employed, either independently or by introducing it from a conduit 37 into the annulus 29 to flow down into the hole along with the deflocculant liquid. A conventional pressure regulator 38 maintains a constant gas pressure in the hole.

Since the deflocculant liquid containing polyphosphates or other deflocculating chemicals is quite valuable, recir-

ulation should be employed, as by pumping used liquid from the slush pit 35 back into the annulus 29. Make-up liquid can be added as needed.

It may be found in some clays that the deflocculant liquid acts so rapidly upon the clay wall of the hole that the proportion of deflocculated clay in the liquid pool 34 becomes too large to handle effectively. When such a situation arises it is desirable to retard deflocculation temporarily by injecting into the hole through the annulus 29 a water solution containing a flocculating material such as sodium or potassium chloride or the other materials mentioned previously herein. After a short time the flow of deflocculating liquid can be resumed. This alternate action of deflocculating and flocculating liquids can be employed as often as necessary to maintain the steady progress of hole enlargement.

After the hole 11 has been enlarged to the desired diameter over the desired length to form a storage cavity 39, the clay walls of the cavity should be treated to assure impermeability, thus to prevent the leakage of liquefied petroleum gases or other liquids which are to be stored. This can be done by impregnating the wall of the hole with a sodium silicate solution to fill up the pores. For example, a water solution containing 10 to 20 percent by volume of a low alkali sodium silicate in which the molecular ratio of silica to sodium oxide falls within the range of from 3.9:1 to 1.5:1 can be introduced into the storage cavity to fill the latter, or can be applied to the walls by spraying it from the ports 31. If the sodium silicate treatment alone is not completely satisfactory, it can be followed by treatment with a solution of a multivalent salt such as calcium or aluminum chloride or a dilute acid solution such as dilute sodium chloride or hydrochloric acid, to precipitate silicic acid or silica.

Another procedure which can be used successfully is to spray such a sodium silicate solution on the walls of the storage cavity through ports 31 while maintaining within the storage cavity a large volume of a gas containing a sufficient quantity of carbon dioxide to react with the deposited sodium silicate and precipitate silicic acid. Such a gas can be introduced from conduit 37 before or after the silicate solution.

Not only should the walls of the storage cavity be rendered as impermeable as possible, but there must also be assurance that further deflocculation will not occur when the cavity is later operated for the storage of fluids. This can be accomplished by applying to the walls of the storage cavity 39 a solution of a flocculating chemical compound such as sodium or potassium chlorides, or any other salt selected from the group consisting of the sodium and potassium thiocyanates, chlorates, iodides, nitrates, bromides, chromates, and chlorides. While even minor quantities of these salts inhibit deflocculation, it is desirable to maintain the salt content of the solution within the range of from 20 percent by weight up to the saturation value of the dissolved component. The salt can be applied as a separate solution or can be incorporated in the sodium silicate solution previously mentioned.

After the storage cavity 39 has been completed as described above, it can be immediately used for the storage of a fluid such as liquefied petroleum gas. The cavity can be filled with a suitable control liquid such as a water solution and the liquefied petroleum gas then pumped down through the annulus 29 to displace solution up through the central pipe 19. When gas later is to be withdrawn from the storage cavity, solution is pumped down through the central pipe 19 and displaces gas up through the annulus 29. In order to maintain the walls

of the storage cavity in a compact and impermeable condition it is advantageous to use as the control liquid a water solution of sodium silicate with or without a flocculant salt of the type described previously herein.

The method of storing liquefied petroleum gases described above also can be used for storing many liquids, as well as gases, which do not adversely affect the walls of the clay cavity. For example natural gas and butane can both be stored as liquids or gases. Also, gasoline and other normally liquid petroleum hydrocarbons can be pumped from the surface of the earth down into such a cavity and stored successfully.

An important advantage of this method of storage is that little if any of the stored fluid is lost due to leakage or evaporation. This is in large part due to the formation of the cavity by washing it out with a water solution, followed by treating the walls to seal them. Any naturally existing pores, fissures or other natural inhomogeneities are filled, covered over and sealed by clay and the sealing chemicals.

This application is a continuation-in-part of application Ser. No. 305,964, filed August 23, 1952, now U.S. Patent 2,803,432, granted August 20, 1957.

Obviously, many modifications and variations of the invention, as hereinbefore set forth, may be made without departing from the spirit and scope thereof, and therefore only such limitations should be imposed as are indicated in the appended claim.

We claim:

A method of operating an underground fluid storage reservoir comprising a cavity in a natural underground clay body beneath the surface of the earth, said method comprising providing in said reservoir a pool of a water solution containing at least one salt selected from the group consisting of sodium and potassium thiocyanates, chlorates, iodides, nitrates, bromides, chromates and chlorides to prevent deflocculation of said clay and keep the walls of said reservoir stable and impermeable, feeding a stream of the fluid to be stored into said reservoir under a pressure sufficient to displace water solution from said pool to the surface of the earth, and subsequently recovering the fluid so stored by feeding a stream of said water solution back into said reservoir under a pressure sufficient to displace stored fluid from said reservoir to the surface of the earth, whereby the walls of said reservoir are kept stable and impermeable.

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## APPENDIX II

### ACID CONSUMPTION OF CLAY SOILS

This appendix presents a report of detailed procedures and results obtained for laboratory tests performed in order to determine the effect of various acids upon clay soil samples. Soil samples used in the experiment were obtained from a site located approximately six miles north of Bryan, Texas, and from a site in the vicinity of Freeport, Texas. Logs of the borings drilled near Bryan are included in Appendix VI. Appropriate cost data are also included. The work was conducted during June and July, 1970, by Dr. Roger D. Whealy, Consulting Chemist, College Station, Texas, for Spencer J. Buchanan and Associates, Inc., Bryan, Texas.

## INTRODUCTION

"Clay" is a name given to a family of soil types. A large number of X-ray diffraction studies have been made of clay, and the general structure has been well defined. The hexagonal sheets characteristic of clay minerals and micas are never found as simple structural units. They are composite layers built up of one or two silicon-oxygen sheets ( $\text{Si}_2\text{O}_5$  groups) combined with layers of hydroxyl groups which are firmly cemented to the silicon oxygen sheets by trivalent or divalent cations, principally aluminum or magnesium in most clays. The general formula  $\text{Al}_2(\text{Si}_2\text{O}_5)(\text{OH})_4$  is an empirical formula which defines the composition of kaolinite. The disintegration of clay would appear to be the elimination of the hydroxyl bonds with acids and/or the complexing of the metal ion. The acid treatment of oil wells is at least a quite similar process and mixtures of hydrochloric acid and hydrofluoric acid are commonly used for this purpose. The hydrofluoric acid will react with the aluminum cation to form the hexafluoro aluminum ion and it will also attack silicon compounds to form either  $\text{SiF}_4$  or  $\text{H}_2\text{SiF}_6$ . This mixture would appear to be the best acid system for decomposing clays. However, it has two disadvantages: (1) It is rather expensive, and (2) hydrofluoric acid is a dangerous chemical to be used by untrained personnel.

### QUALITATIVE DATA FROM SPENCER J. BUCHANAN & ASSOCIATES, INC.

In order to obtain general information on deaggregation of clay soil by the use of chemicals, a number of preliminary experiments were made by S.J. Buchanan and Assoc. The following reagents were combined with water where indicated and added to clay samples, with negative or very incomplete results: (1) concentrated hydrochloric acid, (2) concentrated hydrofluoric acid, (3) 20% by wt. sodium chloride, (4) 20% by wt. potassium hydroxide,

(5) 10% by wt. sodium hydroxide, (6) 10% by wt. polyvinylpyrrolidinone, (7) 20% by wt. dimethylformamide, (8) 10% by wt. sodium phosphate, (9) 15% by wt. Calgon with sodium carbonate, (10) 10% by wt. Calgon with 10% tetrabromethane, (11) 10% by wt. ammonia, (12) 10% by wt. potassium phosphate, (13) 10% by wt. acetic acid, (14) solutions of Calgon ranging from 2% by wt. to saturated, and (15) 25% by wt. Calgon with sodium bicarbonate.

In the same series of experiments dilute solutions of sulfuric, nitric, and monochloroacetic acid were used and the following results were tabulated: (1) an approximate 10% by weight monochloroacetic acid (about 1.5 N solution) destroyed the test cavity clays almost completely in 15 minutes and the Dow clay samples in a few hours time, (2) 28 grams of concentrated nitric acid in 200 ml of water (about 1.4 N solution) destroyed test cavity clay in about 2 hours, (3) 0.1 N sulfuric acid reacted much more rapidly and clay was nearly 100% destroyed in 17 hours, and (6) approximately 13.0 N sulfuric acid destroyed the clay in about 1 hour. In this preliminary work the clay samples had not been weighed but a fair estimate of the weight would be about 125 grams per sample. Although the information from these experiments is somewhat limited there are some rather definite conclusions which can be drawn: (1) acids are effective agents for deaggregating the clays, (2) the rate of decomposition is dependent upon the concentration of the acid present, (3) the total amount of clay destroyed is directly related to the amount of acid consumed (this is not strictly true unless some mechanism is available to rapidly separate the disintegrated solid material from the acid), (4) the individual clay samples reacted quite differently to the acids.

Considering the above facts, it seemed that the next logical step would be to design some experiments which would give more quantitative information concerning the consumption of acid by the different clays.

#### STUDY OF ACID CONSUMPTION OF CLAY SAMPLES

The previously noted experiments conducted by Spencer J. Buchanan and Associates provided considerable qualitative information concerning the problem. The tests demonstrated that several different acids would deaggregate clay, but provided very little quantitative information concerning the amounts of acid needed. The following experiments were instituted to give at least an estimation of the amounts of acid needed and at least a rough estimate of the cost.

Samples of clay, weighed to the nearest 0.1 gram, were placed in reacting vessels and 200 ml. of the dilute acids were added. The sulfuric acid was approximately 3% (v/v) and its concentration was found to be 1.08 equivalents/liter. The dilute hydrochloric acid was approximately 8% (v/v) with normality of 0.968. The nitric acid was approximately 5% (v/v) with a normality of 0.790. The samples containing the sulfuric and hydrochloric acid were analyzed for acid content after both 1 hour and 5 days of contact with the clay. The nitric acid samples were analyzed after 24 hours of contact with the clay. From these data, the information presented in the subsequent tables was calculated.

An unanticipated problem arose in this work. Titration of the acid solutions which had been in contact with the clays revealed that a considerable amount of aluminum and/or iron would react with the base. The acid from the samples was therefore titrated to  $\text{pH} = 3$  with the base. Under these conditions most of the acid would be titrated but reactions

of the hydroxide ion with metal ions would be held to a minimum. The acid concentration was rounded off to the third significant number to either 0 or 5 (perhaps they should be rounded to the second significant number).

Following is a brief explanation concerning the data in Table VI. All of the data shown refer to sulfuric acid ( $H_2SO_4$ ) in contact with ten different clay samples for 1 hour. Approximately 3.0% (v/v) solution of the acid was prepared and the concentration determined to be 1.080 normal. Then 200 ml. of the dilute acid solution was pipetted into each sample containing a known weight of clay. The acid content of the solutions was determined after 1 hour of contact with the clay. The concentrations of the acid, in equivalents/liter, after 1 hour of contact with clay, are shown in column 1. The number of equivalents of acid remaining are shown in column 2 (this is 1/5 th of the number in column one, since 1/5 th of a liter was used). Column 3 shows the equivalents of acid used in the reaction, and was obtained by subtracting the equivalents of acid remaining from the number of equivalents in the original solution.

Column 4 gives the weight of acid consumed, which is found by multiplying the number of equivalents used by the equivalent weight (49.0 for sulfuric acid). The actual weights of the clay samples are shown in column 5. The grams of acid consumed, multiplied by 100 and divided by the grams of clay, are shown in column 6. The following conversion equations were used in calculating the data in column 7:



$$\text{wt. acid in } \frac{\text{lbs.}}{\text{yd.}^3} = \frac{\frac{\text{g. (acid)}}{\text{g. (clay)}} \times \frac{\text{g. (clay)}}{\text{cm}^3} \times \frac{10^3 \text{ cm}^3}{\text{L}^3} \times \frac{764.5 \text{ L}}{\text{yd.}^3}}{453.6 \frac{\text{g}}{\text{lb.}}}$$

If the assumption is made that the clays have a density of  $1.6 \frac{\text{g.}}{\text{cm}^3}$  then the equation simplifies to:

$$\text{weight acid in } \frac{\text{lbs.}}{\text{yd.}^3} = \frac{\text{g. (acid)}}{\text{g. (clay)}} \times 2698$$

This equation was used with 2698 rounded to 2700 in calculation of the lbs. of acid used per cubic yard, which are shown in column 7. The numbers shown in column 8 are the gallons of concentrated acid which would be consumed by one cubic yard of clay in contact with the acid for one hour. These were obtained by dividing the number of pounds per cubic yard by the number of pounds per gallon. The data shown in column 9 are estimated costs for the acid in dollars per cubic yard of clay. They were based on a price of \$0.1775 per pound for sulfuric acid in truckload lots by J.T. Baker Chemical Products. The cost of this "pure" acid is probably much higher than would be incurred by using a low grade acid which would be just as useful for deaggregation of clay. However, the cost of acid delivered in drums is considerably higher than acid delivered in truckload lots. Conversions can easily be made for different acid costs by multiplying the figure in column 9 by the new price quotation divided by \$0.1775.

All data in Table VII refer to 0.968N hydrochloric acid (HCl) which was in contact with the respective clays for 1 hour. The data were compiled in the same manner as for Table VI except that appropriate changes

were made for the different acid constants. The cost calculations shown in column 9 were based on a J.T. Baker price of \$0.2125 per pound. All data in Table VIII refer to 0.79N nitric acid ( $\text{HNO}_3$ ) which was in contact with the clay for 24 hours. The data were compiled in the same manner as the two previous tables except the proper constants were used for nitric acid. The cost data are based on the J.T. Baker price of \$0.235 per pound.

Perhaps the conversion factors involved in the calculation of the data in columns 8 and 9 of Tables VI, VII and VIII should be defined. The data shown in column 7 are the weights of pure acid which react with a cubic yard of clay. The numbers shown in columns 8 and 9 are defined in terms of the usual commercial concentrated acids which are not 100% acid.

For  $\text{H}_2\text{SO}_4$  : approximately 96% pure with density 1.84 g./cm.<sup>3</sup>

$$\begin{aligned} \frac{\text{wt. Pure H}_2\text{SO}_4}{\text{gal. Conc. Acid}} &= \frac{3785 \frac{\text{cm}^3}{\text{gal.}} \times 1.84 \text{ g./cm}^3 (0.96)}{453.6 \text{ g./lb.}} \\ &= 15.3 \frac{\text{lbs. of Pure Acid}}{\text{gal. Conc. Acid}} \end{aligned}$$

To convert the data in column 7 (lbs. of pure acid per cubic yard) to gallons of concentrated acid per cubic yard the number in column 7 should be divided by 15.3.

For HCl : approximately 37.2% pure with density 1.19 g./cm.<sup>3</sup>

$$\frac{\text{wt. Pure HCl}}{\text{gal. Conc. Acid}} = \frac{3785 \frac{\text{cm}^3}{\text{gal.}} \times 1.19 \text{ g./cm}^3 (0.372)}{453.6 \text{ g./lb.}}$$

$$= 3.69 \frac{\text{lb. of Pure Acid}}{\text{gal. of Conc. Acid}}$$

To convert the data in column 7 (pounds of pure acid per cubic yard to gallons of concentrated acid per cubic yard) the number in column 7 should be divided by 3.69.

For  $\text{HNO}_3$  : approximately 70% pure with density 1.42 g./cm.<sup>3</sup>

$$\frac{\text{wt. Pure HNO}_3}{\text{gal. Conc. HNO}_3} = \frac{3785 \frac{\text{cm.}^3}{\text{gal.}} \times 1.42 \text{ g./cm.}^3 (0.70)}{453.6 \text{ g./lb.}}$$

$$= 8.30 \frac{\text{lb. of Pure Acid}}{\text{gal. of Conc. Acid}}$$

To change the data in column 7 (pounds of pure acid per cubic yard to gallons of concentrated acid per cubic yard) the number in column 7 should be divided by 8.30. Since the cost is defined in terms of dollars per pound of concentrated acid, the conversion from pounds of pure acid to pounds of concentrated acid must be made in estimating the cost.

Equation for Cost Determination:

$$(\text{lbs. of Conc. acid}) \times (\text{purity}) = \text{lbs. of pure acid}$$

$$\text{lbs. of conc. acid} = \frac{\text{lbs. of pure acid}}{\% \text{ purity of conc. acid}}$$

$$\text{Cost} = \frac{\text{lbs. of pure acid}}{\% \text{ purity of conc. acid}} \times \text{Cost per lb. of conc. acid}$$

a.) Sulfuric Acid ( $\text{H}_2\text{SO}_4$ ) - 96% pure

The number in column 7 was multiplied by the cost per pound with no correction made for purity.

b.) Hydrochloric Acid ( $\text{HCl}$ ) - 37.2% pure

$$\text{Cost} = \frac{\text{lbs. of pure acid}}{0.372} \times \text{Cost per lb. of conc. acid}$$

c.) Nitric Acid ( $\text{HNO}_3$ ) - 70% pure

$$\text{Cost} = \frac{\text{lbs. of pure acid}}{0.70} \times \text{Cost per lb. of conc. acid}$$

The results of these calculations are shown in column 9.

The data in column 9 of Tables VI and VII indicate that approximately the same amount (in terms of equivalents of acid) of sulfuric and hydrochloric acid react with a given sample of clay. The calculations in Table IX are a method of comparing the amounts of acid reacted in a one hour time period. The data indicate that in each case more sulfuric acid than hydrochloric acid has reacted in this space of time. The numbers are for the most part of the same order of magnitude for a particular clay. Perhaps the difference in consumed acid was due to the fact the sulfuric acid was about 10% more concentrated than the hydrochloric. Also the timing was approximately 1 hour and perhaps the sulfuric acid was actually in contact with the clay a somewhat greater period of time.

The five clay samples 1656, 1657, 1662, 1663, and 1695, are all quite similar in appearance. The acid consumption of the last four in

sulfuric and hydrochloric was quite similar, but vastly different from sample 1656. This was true of both the 1 hour and the 5 day results. However, in the nitric acid the acid consumption was quite similar for all five samples. The three clay samples 2494, 2495, and 2496, are very similar yellow colored clays. Clay sample 2497 is yellow with a chocolate brown tinge. Clay sample 2503 is chocolate brown in color. The variation in acid consuming property is not as great in these five as in the previous samples, but there are some rather marked differences.

One possible explanation of the variations is the presence or absence of shells. Some of the samples contained considerable amounts of shell while others were relatively free from shell. Apparently, the acid first breaks the clay structure, which then exposes the shell that in turn reacts more slowly with the acid. Thus, less acid is consumed in a given period of time.

TABLE VI  
SULFURIC ACID ( $H_2SO_4$ ) CONSUMPTION OF CLAY

Sample Number (1656-1695 from boring at Bryan, Texas) (2494-2503 from boring at Freeport, Texas)	1--Concentration of acid left after 1 hour of clay contact	2--Number of equivalents of acid remaining	3--Number of equivalents of acid reacted in 1 hour time	4--Weight of acid used in one hour time (No. of equivalents X Eq Wt.)	5--Weight of clay sample in grams	6--Weight of acid X 100, divided by weight of clay	7--Weight of acid used in lbs/cubic yard of clay	8--Gallons of concentrated acid per cubic yard of clay	9--Approximate cost of acid in dollars per cubic yard of clay
1656	0.900	0.180	0.036	1.76	120.4	1.47	39.7	2.7	7
1657	0.675	0.135	0.081	3.97	100.2	3.96	107.0	7.3	19
1662	0.540	0.108	0.108	5.29	110.1	4.81	130.0	8.9	23
1663	0.540	0.108	0.108	5.29	100.4	5.27	142.0	9.7	25
1695	0.470	0.094	0.122	6.00	103.7	5.67	155.0	10.6	27
2494	0.800	0.160	0.056	2.74	106.4	2.58	70.0	4.8	12
2495	0.675	0.135	0.081	3.97	104.7	3.79	102.0	7.0	18
2496	0.470	0.094	0.122	6.00	105.5	5.67	155.0	10.6	27
2497	0.745	0.149	0.067	3.28	99.4	3.30	89.0	6.1	16
2503	0.635	0.127	0.089	4.36	108.2	4.03	109.0	7.4	19

Note: 1.) Initial concentration of acid = 1.08 equivalents/liter

2.) Density of clay samples assumed to be 1.6 grams/cc.

TABLE VII  
HYDROCHLORIC ACID (HCl) CONSUMPTION OF CLAY

Sample Number (1656-1695 from boring at Bryan, Texas) (2494-2503 from boring at Freeport, Texas)	1--Concentration of acid left after 1 hour of clay contact	2--Number of equivalents of acid remaining	3--Number of equivalents of acid reacted in 1 hour time	4--Weight of acid used in 1 hour time (No. of equivalents X Eq Wt)	5--Weight of clay sample in grams	6--Weight of acid X 100, divided by weight of clay	7--Weight of acid used in lbs/cubic yard of clay	8--Gallons of concentrated acid per cubic yard of clay	9--Approximate cost of acid in dollars per cubic yard of clay	10--% acid consumed in 5 days
1656	0.840	0.168	0.031	1.13	123.9	0.916	24.8	6.7	14.5	>70
1657	0.620	0.124	0.075	2.74	111.8	2.44	66.0	17.9	38.7	>98
1662	0.470	0.094	0.105	3.82	119.3	3.22	84.0	22.7	47.6	>97
1663	0.595	0.119	0.080	2.92	100.5	2.90	78.5	21.3	45.0	>99
1695	0.520	0.104	0.095	3.46	108.0	3.37	90.5	24.5	51.8	>95
2494	0.745	0.149	0.050	1.83	114.8	1.60	43.2	11.7	24.7	>61
2495	0.670	0.134	0.065	2.37	102.6	2.31	62.1	16.8	35.5	>51
2496	0.415	0.083	0.116	4.23	107.4	3.94	106	28.8	60.6	>99
2497	0.755	0.151	0.048	1.75	114.8	1.53	41.3	11.2	22.5	>47
2503	0.625	0.125	0.074	2.70	111.4	2.42	65.5	17.7	37.5	>97

TABLE VIII

NITRIC ACID ( $\text{HNO}_3$ ) CONSUMPTION OF CLAY

Sample Number (1656-1695 from boring at Bryan, Texas) (2494-2503 from boring at Freeport, Texas)	1--Concentration of acid left after 1 hour of clay contact	2--Number of equivalents of acid remaining	3--Number of equivalents of acid reacted in 1 hour time	4--Weight of acid used in 1 hour time (No. of equivalents X Eq Wt)	5--Weight of clay sample in grams	6--Weight of acid X 100, divided by weight of clay	7--Weight of acid used in lbs/cubic yard of clay	8--Gallons of concentrated acid per cubic yard of clay	9--Approximate cost of acid in dollars per cubic yard of clay
1656	0.094	0.019	0.143	9.0	122.6	7.36	198	24	66
1657	0.091	0.018	0.144	9.0	124.7	7.21	195	23	65
1662	0.095	0.019	0.143	9.0	145.1	6.20	167	20	56
1663	0.094	0.019	0.143	9.0	90.7	9.80	238	29	80
1695	0.096	0.019	0.143	9.0	161.3	5.60	151	18	50
2494	0.380	0.076	0.082	5.1	86.6	5.88	159	19	53
2495	0.350	0.070	0.092	5.8	107.4	5.40	146	17.5	49
2496	0.010	0.002	0.160	10.1	93.2	10.7	289	35	97
2497	0.510	0.102	0.060	3.8	80.8	4.7	127	15	43
2503	0.076	0.015	0.147	9.3	102.2	9.1	248	30	83



TABLE IX  
COMPARISON OF ACID REACTED IN ONE HOUR

Sample Number	Eq. of reacted ( $\text{H}_2\text{SO}_4$ ) $\times 10^4$ per gram of clay	Eq. of reacted ( $\text{HCl}$ ) $\times 10^4$ per gram of clay
1656	3.0	2.5
1657	8.1	6.7
1662	9.8	8.8
1663	10.8	8.0
1695	9.1	8.8
2494	5.3	4.4
2495	7.7	6.3
2496	8.9	7.7
2497	6.7	4.2
2503	8.2	6.6

### DISCUSSION OF RESULTS

All of the data indicate that a certain level of acid concentration is necessary to provide a reasonable reaction rate. In 0.1 N acid the reaction is proceeding but at a slow rate. Although there is no great decomposition of the clay in these acid solutions, the pH of the solution continues to rise to a final value between  $\text{pH} = 3$  and  $\text{pH} = 4$ . In the solutions of strong acids (sulfuric, nitric, hydrochloric), which were originally about 1.0 N, the reaction apparently was complete when the solution had a pH of about 1.0. In the case of the 1.0 N weak acid (monochloroacetic -  $K_a = 1.5 \times 10^{-3}$ ) the pH of the solution after several days contact with clay was in the pH range of 2.5 to 3.5. All of these data are fairly consistent with the idea that the final total consumption of acid is independent of the type acid present.

The data in columns 7 of Tables VI and VII indicate that sulfuric acid will react with clay more rapidly than hydrochloric acid. However, this interpretation is not essentially conclusive. There are several possible explanations for these results. The sulfuric acid was approximately 10% more concentrated than the hydrochloric and previous results have indicated that the reaction rate was dependent on the concentration of the acid. In most of the samples, the variation between the two acids in acid consumption during the first hour, was less than 10%. Also, the timing was not exact and the sulfuric acid may have been in contact with the clay a slightly longer time. The actual differences noted are probably not significant.

The very large differences in acid consumption for nitric acid which was in contact with the different clays for 24 hours as compared to the

acid consumption of sulfuric and hydrochloric in contact with the clays for 1 hour are highly significant. This clearly shows that the total acid consumption will, to a great extent, depend upon the time the acid is in contact with the clay. The relatively small differences in acid consumption for the sulfuric and hydrochloric acids for one hour are probably not significant.

A number of factors will affect the optimum conditions for decomposing clay. The first, and perhaps the most important, is the nature of the clay. If it contains relatively large amounts of extraneous materials which will react with acid, such as carbonates, it may disintegrate the clay rapidly but continue to react with these compounds. Under this condition the most important factor would be minimizing the total time the acid is in contact with the clay. If a given clay had small amounts of material, other than the clay, which would react with acid, then time ceases to be an important factor.

The concentration of the acid used will be a factor. The rate of disintegration will in general be related to the acid concentration. Greater concentration will result in faster disintegration and the excess acid and solid material can be removed from the cavity more rapidly, thus decreasing the total time the acid is in contact with the clay. This will be particularly important if the clay contains a large amount of extraneous material which reacts with acid. Most of the sea shells, etc., are not really exposed to the action of the acid until the structure of the clay is broken down.

If a recycling process is to be used, it is important that the acid in holding tanks be isolated from the clay as rapidly as possible. The important thing is the total time the acid is in contact with the clay,

whether in the cavity or in the holding tank.

The data indicate that hydrochloric, sulfuric, nitric, and monochloroacetic acids could all be used to decompose the clay. The factors which should be considered in selecting the particular acid are cost, hazard to operators, ease of handling, waste disposal problems and effect on machinery involved. The four acids are discussed in terms of these factors with the omission of the machinery question.

Serious consideration was not given to the monochloroacetic acid. It would be the most expensive reagent to use, it is very poisonous, and there would be a serious problem in disposing of the waste product. Its single advantage would be in ease of handling because the acid is in crystal form at ambient temperature.

Nitric acid is less desirable than either sulfuric or hydrochloric. It is more expensive, and it is a more hazardous chemical in the hands of unskilled or semiskilled operators than either of the other two acids. Its one real advantage would be in the ease of disposing of the waste product. The excess acid could be neutralized with lime or other strong base, and then diluted with water to give a harmless solution.

Hydrochloric acid could be a possible choice. The data indicate that it would be about twice the cost of sulfuric. The hydrochloric acid is much less hazardous in the hands of unskilled operators than any of the other acids. A mask to protect the eyes and the respiratory tract, and sufficient water to remove any acid spilled or sprayed on the body of operators would be essential. The disposal problem with hydrochloric acid would be minimal. The acid could be neutralized with lime or other strong base and diluted with water to a harmless solution. The hydrochloric

acid would be the easiest reagent for unskilled or semiskilled people to use.

Sulfuric acid would be the least expensive acid to use by a rather wide margin. Although sulfuric acid is less hazardous than nitric acid, untrained people should study carefully some manual on the handling of sulfuric acid. The book Sulfuric Acid by Fasullo is probably the best source of information. There are no serious disposal problems with this acid. In some samples containing large amounts of calcium, considerable amounts of calcium sulfate would be produced. This could be buried without harm to the surroundings. The principal problem with this acid would probably be in its corrosion of machinery. Information from petroleum companies could perhaps answer this question.

One other qualitative observation was made in this work. Clay has a structure similar to mica and there is a strong tendency in some of the samples to first separate as sheets of material, quite large in area but with small cross section. This might lead to a serious problem in developing a well defined cavity of even approximately the shape desired. When the clay has disintegrated into these sheets it opens up avenues of lateral movement. It was also noted that clays which had a relatively large sand content decomposed very rapidly. This might lead to "pocket formation" and rather drastic changes in cavity shape. These are qualitative observations and perhaps there are practical answers to these problems.

Another practical problem is the generation of gaseous materials. In the presence of carbonaceous compounds the acid will react to generate carbon dioxide gas. The extent of gas formation would depend upon the amount of carbonaceous material present in the clay. In some of the laboratory samples there was very little carbon dioxide produced whereas

in others a very large amount. The acids will also react (at least to some extent) with the metal parts of the drilling rig to produce hydrogen gas. Some information concerning this could probably be obtained from companies involved in acid treatment of petroleum wells.

### CONCLUSIONS

It is always difficult to extrapolate a restricted laboratory experiment to a practical engineering situation and this is particularly true here, because of the many variables which have not been examined. This was a laboratory experiment to determine the acid consumption of clays. It has shown there is a wide variation in acid consumption from one sample to another. There apparently is no real difference in the equivalents of acid used for a given mass of clay between the strong acids. The rate of decomposition of the clay is directly related to the concentration in dilute acid solutions. Cost estimates were made for the three acids--sulfuric, hydrochloric and nitric. From this study, it would appear that hydrochloric or sulfuric acid would be the possible best choices. The sulfuric would be least expensive in terms of the acid cost only. The sulfuric acid is a more hazardous material for personnel to handle than hydrochloric acid. The sulfuric acid is a more corrosive material and might cause serious problems with drilling apparatus. This factor should probably be investigated thoroughly. The most reliable source of information would be the companies involved in acid treatment of oil fields.

### APPENDIX III

#### A. B. FLY HYDRO-JET TECHNIQUE

This appendix includes various details of the A. B. Fly hydro-jet mining procedure as presented in "Subsurface Hydraulic Mining through Small Diameter Bore Holes," Paper B1, Hydrotransport 1, First International Conference on the Hydraulic Transport of Solids in Pipes, September, 1970. Also included is correspondence from Mr. A. B. Fly, Hydro-Jet Services, Inc., Amarillo, Texas.



HYDROTRANSPORT 1

PAPER B1

FIRST INTERNATIONAL CONFERENCE  
ON THE HYDRAULIC TRANSPORT  
OF SOLIDS IN PIPES

1st - 4th SEPTEMBER 1970

# SUBSURFACE HYDRAULIC MINING THROUGH SMALL DIAMETER BORE HOLES

A. B. Fly, B. S.

Hydro-Jet Services, Inc., United States.

## Summary

This paper presents the equipment and techniques developed to mine subsurface mineral deposits through 16 inch bore holes entirely by hydraulic methods. Use of this equipment for excavating large cavities in oil and water well producing zones is discussed. Results of surface experiments using high pressure jet streams of water to determine the cutting rates of materials are outlined. Various basic shapes of subsurface excavations that can be mined with the equipment are illustrated and discussed. An example of the cost of mining by this method is presented. Consolidated sandstones, weathered limestones and laminated shales have been mined by the method presented. Mining operations have been conducted to depths of 350 feet. Mining rates of one cubic yard per minute have been achieved under field conditions. A volume of 450 cubic yards of material was removed from one bore hole. Cavities have been excavated to a lateral distance of 30 feet from the bore hole. Problems encountered in the field operations led to the development of a new explosion type slurry pumping system and related slurry handling equipment. Slurry concentrations of 60 percent solids by weight have been successfully pumped using the explosion type pumping system.

Held at the University of Warwick.

Conference sponsored and organised by the British Hydromechanics Research Assn., Cranfield, Bedford, England.

Subsurface hydraulic mining through small diameter bore holes was developed primarily to increase the fluid production from irrigation wells, to mine subsurface mineral deposits, and to perform miscellaneous subsurface excavation operations. Increasing the fluid production from oil and water wells has been the only field application of the process to date. Mining of a uranium bearing Morrison sandstone formation is planned by the company in 1971 in the Henry Mountain Mining District in Garfield County, Utah. Miscellaneous subsurface excavation operations that have been considered include LPG storage caverns, atomic waste disposal caverns, and underground storage rooms.

Bore hole mining combines the principles of hydraulic mining, slurry mucking and rotary drilling. The bore hole is drilled with conventional equipment and is cased down to the top of the mining zone. The overall system is illustrated in Figure 1 which shows the equipment being used to excavate an underground storage cavern. The mining tool is comprised of the Kelly-swivel assembly, multiple drill pipe sections, and the jet pump barrel assembly as shown in Figure 2. The kelly swivel is fitted with a bail to support the mining tool. The kelly drive bushing engages the rotary table to allow the rotation of the mining tool while it is being operated. The jet pump barrel assembly is comprised of the sidewall jet nozzles, the jet pump assembly, the suction screen, and the tri-cone rock bit.

Following the fluid flow from the settling pits, the clean fluid is pumped at high pressure through the kelly hose to the high pressure swivel on the mining tool. The high pressure pipe conducts the fluid down to the sidewall jet nozzles, the jet pump nozzle, and the tri-cone rock bit. The sidewall jet streams cut the formation and wash the cuttings down to the rock bit. High pressure fluid issues from the water courses to clean the bit and to agitate the cuttings. Rotation of the mining tool causes the rock bit to grind any oversize material sufficiently to pass through the suction screen. High pressure fluid issues from the jet pump nozzle to provide the lift to pump the slurry to the surface. The slurry is discharged into the settling pits where the cuttings are deposited and the clean fluid returned to the suction of the high pressure pump.

Mining preparations would first involve determining the desired mining rate, the required flow through side wall jets to accomplish that rate and the required flow through the pump jet nozzle to lift all fluids and cuttings to the surface. Mining rates up to one cubic yard per minute have been achieved mining Tertiary sandstones, weathered Cretaceous limestones and laminated Triassic shales. Flow rates through the sidewall jet nozzles to accomplish these mining rates have averaged 400 GPM at 800 PSI. Flow rates through the water courses of the rock bits have averaged 100 GPM at 800 PSI. The required flow rate through the pump jet nozzle increases with the mining depth and must be properly sized to lift all fluid and cuttings to the surface as fast as they accumulate in the bore hole. The fluid level in the bore hole must be maintained below the sidewall jet streams at all times to achieve maximum mining rates. At a mining depth of 200 feet, approximately 500 GPM at 800 PSI would be required through the pump jet nozzle to lift one cubic yard of cuttings and 500 gallons of mining fluid per minute. The mechanical efficiency of the jet pumps that have been used have averaged about 35 percent which results in large hydraulic horsepower requirements. An air lift pump has been used in conjunction with the jet pump to reduce the hydraulic horsepower requirements on the deeper mining operations. Compressed air was supplied to the air lift pump head through a third pipe passing down through the center of the pressure pipe. Calculations have shown that the combination of the jet pump supplying the submergence head to the air lift pump would be feasible for mining operations to depths of 1500 feet. Pressurization of the bore hole with compressed

air to reduce the lift horsepower requirements have been accomplished using a rotating packer to seal the annulus between the kelly and the well casing. Based on calculations, the combination of the three lifting systems would be feasible for mining small cavities to depths of 7500 feet.

Mining rate estimates can be made from small scale jetting tests and detailed mechanical properties tests on cores of the formation. Where large representative samples of the formation are available from outcrops or conventional mining operations, full scale jetting tests should be conducted. A large jetting test stand has been constructed to handle two-foot cube samples of the formation and test the cutting rates to thirty foot radial distances. Jetting tests have been conducted on samples prepared from a 5:1 portland cement-sand mixture cured for seven days. Cutting rates of six cubic yards per hour were achieved on these samples at a radial distance of 15 feet. Cutting rate tests were also conducted on Selma chalk samples. Due to low permeability and closed cell structure of the Selma chalk, several changes in mining techniques had to be implemented to achieve economical mining rates. These changes included raising the sidewall jet stream velocity from 325 feet to 400 feet per second and cutting the chalk into six inch slabs which would then be ground to minus one inch particles by the rock bit. Mining rates were estimated at one half cubic yard per minute using these techniques. Mining rate tests have not been conducted using suspended abrasive particles in the jet streams due to the maintenance problems involved when using conventional high pressure pumps. However, the recent development of the Hydro-Torq explosion type pump will allow the recirculation of abrasive particles without incurring any high maintenance problems. The mining tool has been redesigned to permit the separation of the abrasive particles from the main fluid stream and to direct the flow of the particles into the center of the sidewall jet streams. Mining rate tests are planned to evaluate this technique. Where sufficient abrasive particles of the proper size are not available in the cuttings, steel shot up to 1/4 inch diameter can be substituted. The steel shot could be recovered from the return cuttings for recirculation. Mining rates of hard, brittle formations should be substantially increased by this technique.

Various basic shapes of subsurface excavations that can be mined by this system are illustrated by figure 3. The circular disc cut with a flat roof and cone shaped bottom would be used where the roof strength was adequate to prevent caving. The multiple narrow trench cuts have been used to increase the production rates of oil and water wells. The cylindrical tank cut with a dome shaped roof and conical bottom would be used for underground storage vessels. The wide trench cut would be used in mining a vein of ore. Combinations of these basic cuts can be employed with a high degree of accuracy. Vertical orientation of the sidewall jet streams can be controlled within approximately two inches. Azimuth orientation can be controlled within approximately one degree.

Bore hole mining of caverns and lateral trenches into the sidewalls of irrigation wells and one oil well has been the only field application of the process to date. Production from oil and water wells can be substantially increased by excavating multiple narrow trenches back into the production zone as illustrated in Fig. 3. Production increases on irrigation wells have closely followed Darcy's Law for perched water conditions as follows:

$$Q = \frac{\pi P (D^2 - d^2)}{\log e \left( \frac{R}{r} \right)}$$

Q = Gal. Per Day  
P = Permeability  
D = Saturated Thickness  
d = D - drawdown  
R = Radius of Influence  
r = Radius of Well

It can be seen from this formula that a fifty fold increase in the effective radius of the well will greatly increase the flow rate. Increases as high as 550 percent have been accomplished on small irrigation wells producing from a tight Tertiary sandstone formation. The bore holes were generally underreamed out to 4 to 10 feet in diameter prior to starting the trenching operations. Four lateral trenches approximately one foot wide, twelve feet high and thirty feet in length were excavated in the lowest producing zone of most of these wells. Penetration distances were calculated from the volume of cuttings removed from the bore hole. Excavation rates as high as one cubic yard per minute were achieved during these operations excavating Tertiary sandstones, Cretaceous limestones and Triassic shales. A total of four hundred fifty cubic yards of cuttings were removed from one irrigation well during these trenching operations. Only one shallow oil well has been underreamed using this equipment. This well was producing from the Paluxy sandstone in Edwards County, Texas at a depth of 332 to 342 feet. Average production from wells in this area is approximately one barrel per day of 16.7 gravity oil. Six trenches one foot wide, ten feet high and fifteen feet laterally were cut into the pay zone removing a total of sixty eight cubic yards of cuttings. Initially the production was increased to eight barrels per day but was subsequently reduced to three barrels per day due to the formation of a fresh water-oil emulsion in the faces of the trenches.

Some of the problems encountered during field operations were: excessive maintenance costs on the high pressure pumps; unloading the compacted cuttings out of the steel settling tanks; pumping the water level down in the larger cavities; accumulation of large cobbles in the sump when mining conglomerate formations and excessively high cutting rates in the softer formations. Both duplex piston and multistage centrifugal pumps have been used to power the mining tool. Excessively high maintenance costs were encountered with both types of pumps due to the recirculation of abrasive silts and fine sands. Standard oil field steel mud pits were used and did not afford sufficient settling area at these high circulation and mining rates. Many innovations were attempted to reduce the maintenance costs with very limited success. This problem finally forced the development of the Hydro-Torq explosion type pump which will be discussed below. Jetting the cuttings out of the steel mud pits was a major problem due to the extremely compact settling of the cuttings. This problem was finally solved by fluidizing the settled cutting along the floor of the steel pits. Fluidization was accomplished by pumping at high rates through multiple valves along the floor causing the compacted cuttings to slump and flow to the suction of the pit jets. Pumping the water level down in the larger cavities following a shut down required considerable time. The largest cavity excavated held approximately 90,000 gallons and the formation produced approximately 150 gallons per minute additional water. In most mining operations of water saturated ores, fluid production would not be a major problem due to the lower permeabilities generally encountered. Accumulation of large cobbles in the sump when mining conglomerate formations required that sufficient storage volume be provided by underreaming of the sump hole to a larger diameter. Excessively high cutting rates in the softer formations resulted in sanding down the jet pump during the initial operations and was solved by developing an electrically operated down hole valve to turn the sidewall jet streams off when slurry concentrations were excessive. This valving system was also needed during trenching operations to enable the driller to turn the sidewall jet streams off during the mucking operations, and on again after re-indexing on the trenches being excavated.

The Hydro-Torq explosion type pumps were developed to provide a high pressure pumping system with a minimum of moving parts that contacted the abrasive laden fluids. This was accomplished by combining the engine and pump into one machine.

The basic operational cycle of the system is illustrated in Fig. 4. Fluid enters through the suction valve filling the pump cylinder to the desired level while the exhaust valve is being held in the open position. After the exhaust valve is closed, the fuel-air mixture is injected into the cylinder at the desired pressure. When the intake valve closes, the spark plug ignites the fuel-air mixture and the resulting explosion drives the fluid out through the discharge valve at high pressure. Opening of the exhaust valve releases the residual exhaust gas pressure from the cylinder through an air compression system which is not illustrated. Hydro-Torq slurry pump units are comprised of six of these cylinders, each of which is a combination internal combustion engine and reciprocating pump. All six cylinders are coordinated to fire at equal intervals by the electrical and hydraulic systems which opens and closes the engine valves in proper sequence. Any individual cylinder can be shut down for complete repairs while continuing to pump with the remaining five cylinders firing at a slightly faster rate. Rate of firing and power per cycle can both be varied to control total displacement and discharge pressure. Liquid fuel injection or vapor fuel metering systems can be provided for the particular fuel to be burned. Methane, propane, butane, and gasoline have been used during the previous slurry pumping tests with negligible combustion products contamination of the slurries. Additional fuels that will be tested in these pumps include diesel, fuel oils, diesel-coal dust slurries, and superheated water-coal dust slurries. Overall thermal efficiency testing using various fuels and varying slurry pumping parameters are planned in depth for the near future. Floating pistons can be provided in the cylinders for maximum fuel efficiency and slurry displacement as needed. Slurry concentrations up to 60 percent by weight (minus 4 mesh) have been pumped with negligible wear and no appreciable degradation of the slurry. Extremely abrasive, fast settling slurries have also been pumped successfully. Changes in the basic fluid-valve design have been made and partially tested that should permit the pumping of slurries containing particles as large as one inch in diameter. Utilization of this pumping system is planned for powering the mining tool while circulating abrasive particles through the sidewall jet streams. Utilization is also planned for long distance solids pipelining of mineral ore slurries from either subsurface hydraulic mining or conventional mining operations which offers substantial savings in transportation costs. Slurry mucking and slurry hoisting operations are other areas of possible utilization in conjunction with both underground mining and tunnel drilling operations to alleviate space and equipment capacity limitations.

Mining operations would be initiated by excavating the cone shaped sump in the underlying formation to facilitate the return of the cuttings and fluids to the jet eductor suction. Excavation of a dome shaped cavity above the mineralized zone may be necessary to prevent caving of the overburden and dilution of the ore in some formations. Following these preparatory cuts, hydraulic mining of the mineralized zone would be initiated making progressive cylindrical cuts until the desired radial mining distance had been achieved. Bore hole spacing could be maintained to leave pillars between adjacent bore holes to support the overburden similar to room and pillar mining. The pillars could be mined out using additional bore holes drilled through the center of each pillar. Longwall mining methods can be approximated using a progression of square cut mining patterns allowing the overburden to cave behind the mined out area.

Mining of subsurface mineral deposits will require detailed exploration work to define the ore body, an evaluation of the bore hole drilling costs and estimates of the optimum mining rates and costs. Definition of the ore body should include the value per ton, thickness, areal extent, dip, strength of the overburden, permeability, porosity, hardness index, compressive strength, fluid production estimates

if saturated, and the character of the underlying strata. Lenticular deposits that are more than six feet thick would be the most amenable to this system of mining. Approximately 220 tons of formation can be mined for each foot of thickness using a sixty foot diameter circular mining pattern. Bore hole drilling cost estimates should include drilling the bore hole to depth of twenty feet below the mineralized zone, setting casing down to the top of the mineralized zone and pulling the casing after the mining operations are completed.

An example of the operating costs of mining ore by this method can be made by assuming an ore deposit 10 feet thick at a depth of 200 feet. Operating costs will be projected for the mining operations on a single bore hole. A 19 inch bore hole would be drilled to a depth of 230 feet. Sixteen inch casing would be suspended in the bore hole to a depth of 200 feet. The mining tool would be used to excavate the cone shaped sump and to mine the ore deposit from a circular area 60 feet in diameter. The mining rig would then be moved 60 feet to the next location. After the mining operations were completed, the casing would be pulled from the bore hole for reuse. Approximately 28,270 cubic feet of ore weighing 2200 tons could be mined from each bore hole. Assuming an average mining rate of one half ton per minute, approximately 75 hours would be required. Power requirements circulating 1,000 GPM at 800 PSI would be 465 hydraulic horsepower. Other requirements common to several bore holes in an area will be prorated in these estimates.

#### ESTIMATED OPERATING COSTS FOR MINING 2,200 TONS

Drill 19 inch bore hole to 230' @ \$7.50/ft.	\$ 1,725.00
Install & Recover 200' of 16" casing @ \$2.50/ft.	500.00
Labor & Supervision for mining - 105 hrs. @ \$15.00/hr.	1,575.00
Power Requirements - 465 HHP X 100 hrs. X \$0.03/HHP/hr.	1,395.00
Depreciation, Maintenance, Taxes and Insurance	850.00
Roads, Water, Pits, Transportation & Miscellaneous	475.00
Total Operating Costs	\$ 6,520.00
Estimated Cost Per Ton	\$ 2.95

These estimates are presented only to outline the general parameters affecting the overall cost of mining by this method. Bore hole expenses in this example represent approximately 35 percent of the total costs. Mining rates and the recoverable tonnage from each bore hole are the next most important parameters. The mining rate assumed in this example is approximately one third of the rates that have been achieved in the field. An increase of only 10 feet in the diameter of the circular mining pattern would increase the recoverable tonnage by 35 percent.

Bore hole mining offers several important advantages over conventional mining under favorable geological conditions. Immediate production of the highest grade ore would substantially reduce the initial capital requirements. High rates of production could be achieved with a minimum of labor and equipment. Small isolated ore bodies could be mined without a material increase in mining costs. Many underground hazards are eliminated, allowing the development of unstable, gaseous, or water saturated deposits. Crushing and grinding costs are substantially lowered with some formations being reduced almost to grain size by the jet streams. Slurries from the bore hole mining operations would be an ideal feed for on-site hydrometallurgical milling operations. Tailings from the milling operations could be pumped back into the mined out caverns to control subsidence and reduce the waste disposal problems. Overall mining and milling costs could be very competitive with conventional methods under favorable conditions allowing the development of some presently sub-economic mineral deposits.

### CONCLUSIONS

Evaluation of the mining methods available for the recovery of an ore deposit from shallow depths should include subsurface hydraulic mining through small diameter bore holes. Evaluation of the ore transportation and hoisting methods available should include the explosion type slurry pumping system. These systems will be found to be the most economical methods for many operations.

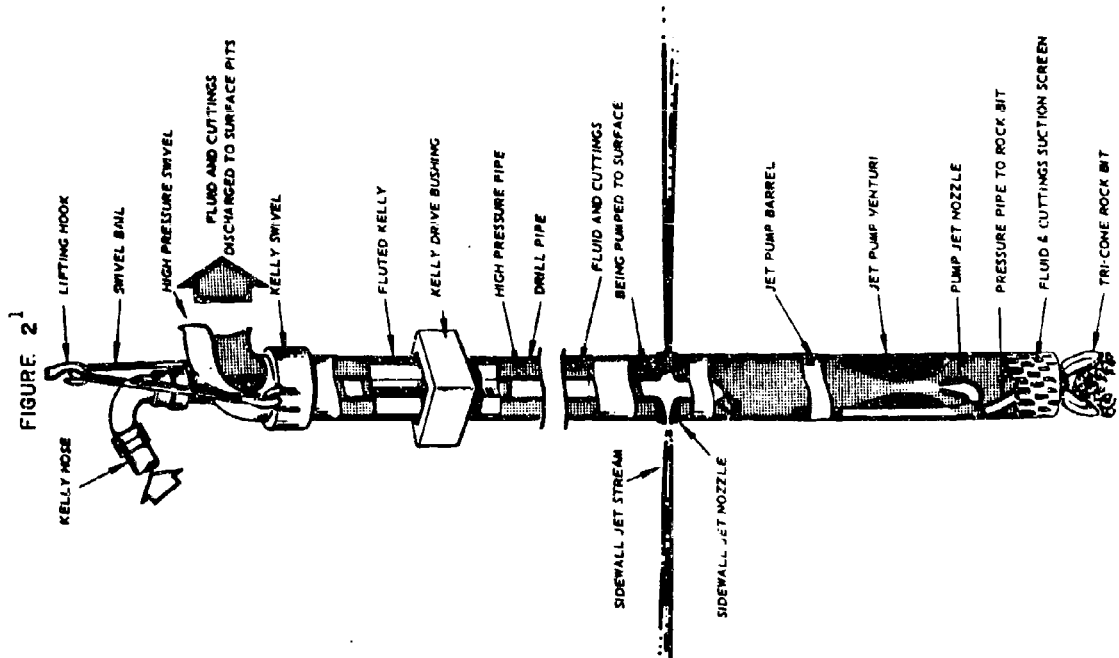


FIGURE 16. HYDRO - JET HYDRAULIC UNDER-REAMER

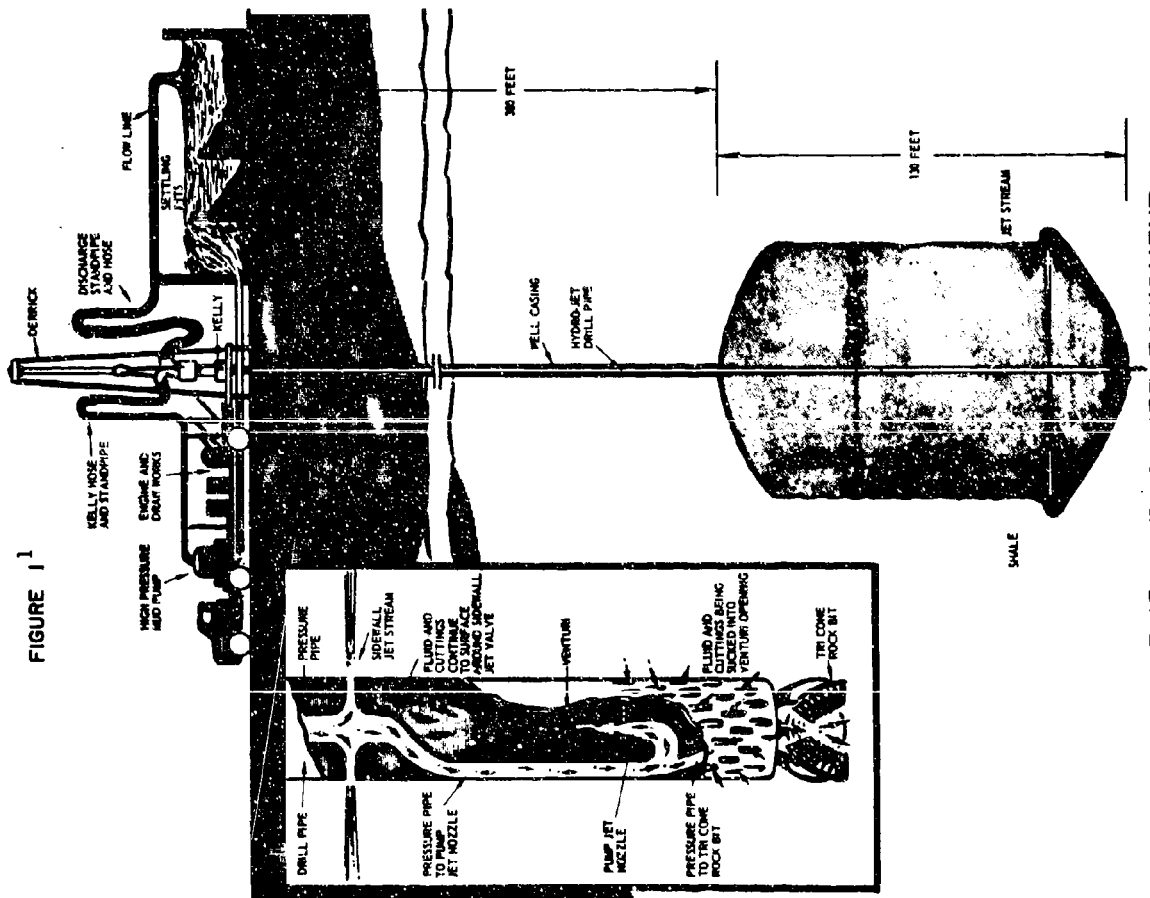


FIGURE 15. HYDRO - JET EQUIPMENT

These figure numbers refer to Appendix III text.



FIGURE 3<sup>1</sup>

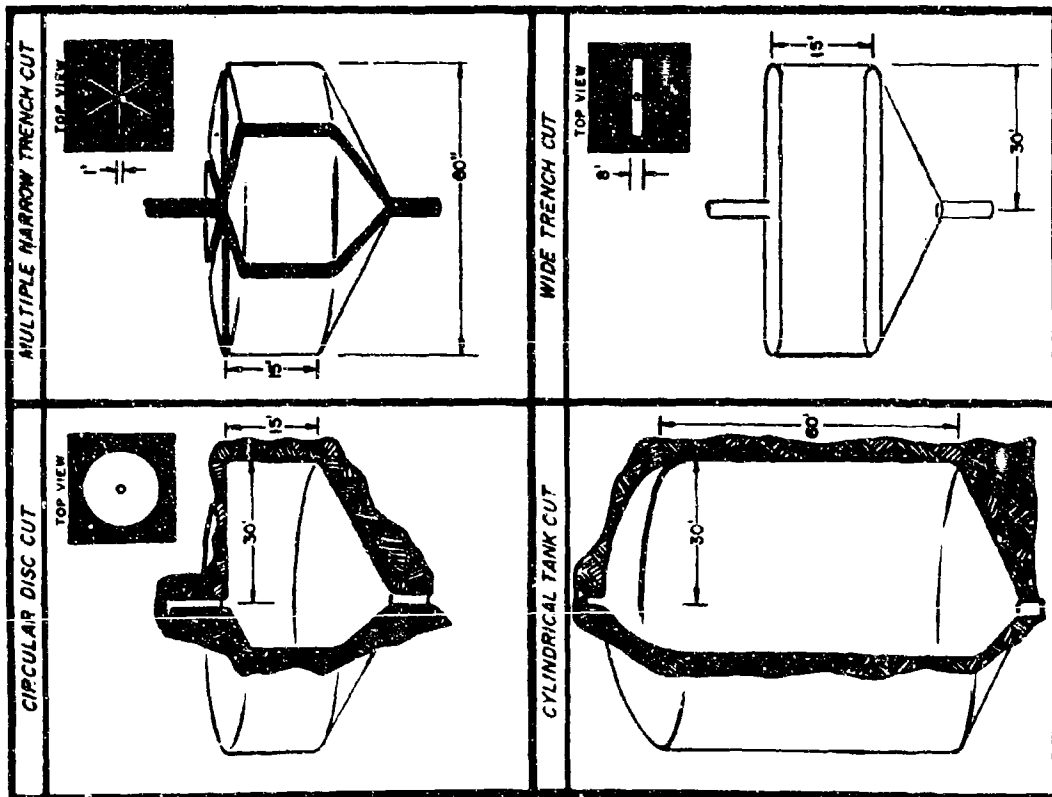


FIGURE 17. BASIC SHAPES OF SUBSURFACE EXCAVATION

FIGURE 4<sup>1</sup>

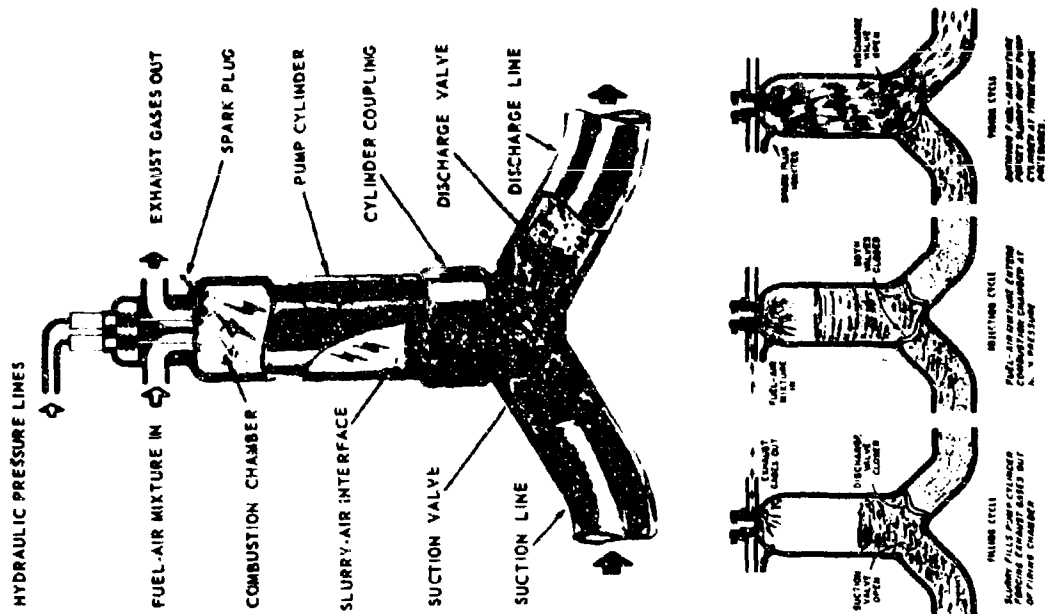


FIGURE 18. HYDRO-TORQ EXPLOSION PUMP

<sup>1</sup> These figure numbers refer to Appendix III text.



**HYDRO-JET  
SERVICES, INC.**

**BOX 808**

**AMARILLO, TEXAS**

**DR4-3594**

79105

February 15, 1971

Col. Joe R. White  
Spencer J. Buchanan & Associates, Inc.  
Consulting Engineers  
P. O. Box 672  
Bryan, Texas 77800

Dear Col. White:

We have designed a new Raise Boring system which we feel could reduce raise boring costs by as much as 30 percent. The primary advantages of the Hydro-Jet Raise Boring System would be as follows: all equipment would be rail mounted and could be moved readily through minimum size drifts; the boring equipment could be set up and operated by a two man crew in a minimum size rock cut out; blind raises up to 84 inches in diameter could be bored from beneath the ore body at any desired angle up to 30 degrees off vertical; all muck would be dewatered and loaded directly into a series of standard ore cars; the ore cars and all equipment on trackage could be readily disconnected and moved to allow passage through a drift; the electrical power, compressed air and water requirements could be adjusted to prevent overloading of the normal mine supplies; the equipment could also be used to drive blind headings to connect ore passes to service entrances, where the terminal ends of the two blind raises were located within 40 feet of one another; and the equipment could also be used to actually mine small isolated ore bodies.

Most of the engineering principles involved have already been field tested in the development of our system for "Subsurface Hydraulic Mining thru Small Diameter Bore Holes" which is described in the enclosed literature. The Hydro-Jet Raise Boring System is basically a modification of the bore hole mining equipment to facilitate working underground in a vertical position. All of the technology already developed in the areas of nozzle design, rock breakage, primary reduction of muck size, slurry blending, slurry handling, slurry dewatering, fluid reclamation, high pressure pumping, and drill string orientation are directly applicable to raise boring problems.

A simplified schematic diagram of the raise boring system is also enclosed which illustrates the equipment layout for boring 52 inch diameter raises. The raise boring system would be sufficiently automated to automatically control all fluid levels, muck levels, fluid pressures and flow rates throughout the entire system. Boring of 52 inch diameter raises in soft to medium hard permeable sandstone formations should proceed at a minimum average rate of 6 feet per hour. The maximum permissible cutting rate would be approximately 40 feet per hour using 500 horsepower input to the cutting head. The estimated moving time to rigdown, move forward to the next cut out and rig up to bore the next raise would be approximately 8 hours.

February 15, 1971

Raise boring operations would be initiated by air drilling an 8-5/8 inch pilot hole to the maximum raise height desired. The cutterhead assembly and the roller cutter underreamer would then be installed to ream the pilot hole to the desired raise diameter. Rock would be broken from the raise walls by impingement with high velocity steel shot and two jet streams of water. Cuttings and shot would be washed down to the underreamer, crushed to - 3/4 inch against the wall of the pilot hole and then, gravity flow downward to the slurry handling system. The steel shot would be removed from the slurry line thru a hydraulic classifier which is not shown on the raise boring system diagram. The shot would be washed, screened, and recirculated thru the steel shot nozzle in the cutterhead assembly at rates up to 100 shot per second and velocities up to 1,200 feet per second. Thickened slurry from the 6 desander units would be loaded directly into 12 ore cars. Surplus water from the ore cars and the desander units would be pumped thru the desilting cones into the head tank car for de-aeration and recirculation. Slimes from the desilting cones would be entrained with the coarse muck in the ore cars to eliminate discharging any waste fluids into the mine drainage system.

Also enclosed is a simplified schematic diagram of the Hydro-Jet Drifting System which illustrates the equipment layout for driving a 7 X 9 foot drift using the same basic equipment. The rock would be broken from the drift face by impingement of high velocity 3/8 inch steel shot and a jet stream of water which would be directed and controlled by the equipment operator. Rock cuttings and steel shot would be washed down to the 48 inch roller bit which crushes the cuttings to -3/4 inch against the drift floor. The blended slurry would be jet pumped back past the track laying area to the slurry handling system. The steel shot and the slurry would both be processed in the same manner as described above for the raise boring operations. The maximum permissible drifting rate would be approximately 8 feet per hour of 7 X 9 foot drift in soft to medium sandstones.

Another application of bore hole mining technology to conventional underground mining problems would be the sinking of exceptionally large diameter shafts. The desired diameter of the shaft could be controlled within - 0.0 to + 12.00 inches using the cutting range control system which turns off the jet streams individually to prevent cutting the shaft to oversize. Sinking of large diameter shafts in extremely unstable ground could also be accomplished.

These systems could be made available on either a day work basis, a footage contract basis, or on a lease basis with all normal equipment maintenance furnished. We would need sufficient day work, footage contracts, or long term lease contracts to justify tooling up the remainder of these systems.

Detailed information that would be needed to evaluate your requirements is as follows: mines to be worked; shafts to be worked; drifts to be worked; number of raises in each drift; spacing of raises along each drift; accurate logs of all drill holes and long holes in the immediate vicinity; availability of trackage, ore cars, electrical power, compressed air, and water at each mine; an appraisal of any tramming and hoisting limitations; and a detailed

Col. Joe R. White

-3-

February 15, 1971

time schedule of all work to be done. Any information which you forward to us will be handled in the strictest confidence and used only to evaluate your requirements. Our completed evaluation and recommendations for your program would be forwarded to you and then followed up with a personal visit to your mines.

We are planning to conduct additional mining rate tests on large samples of welded volcanic tuff, dolomite, Selma chalk, and hard bauxite in the near future at our yard in Amarillo. We would like to extend our invitation for you or your representative to attend these tests. The steel shot fracturing system will also be employed and the bore hole mining equipment could be observed at that time.

Sincerely,

HYDRO-JET SERVICES, INC.

*A. B. Fly*  
A. B. Fly  
President

ABF:ew

Encl.

# GENERAL SPECIFICATIONS

MIN. ROCK CUT OUT REQUIRED (FT)	6 L X 6 W X 10.5 H
MAX. RAISE BORING HEIGHT	208 FT
MAX. RAISE DIAMETER	84 IN
MAX. RAISE BORING RATE (52 IN)	40 FT/HR
MAX. OFF VERTICAL ANGLE OF RAISE	30°
MAX. HEADING CUTOUT AT TOP OF BLIND RAISE (FT)	7 W X 9 H X 20 L
AZIMUTH ORIENTATION OF BLIND HEADING	±2°
ELECTRICAL POWER REQUIREMENTS	35 TO 125A @ 4160V 3Ø
COMPRESSED AIR REQUIREMENTS	300 TO 720 CFM @ 80 PSIG
WATER SUPPLY REQUIREMENTS	20 TO 50 GPM
EST. TOTAL UNDERGROUND EQUIPMENT WEIGHT	33,000 LB
EST. TIME TO MOVE IN FROM SURFACE & RIG UP	8 HRS
EST. AVG. TIME TO BORE 100 FT OF 52 IN RAISE (2 MEN)	16 HRS
EST. TIME TO RIG DOWN & MOVE OUT TO SURFACE	2 HRS
EST. TIME TO RIG DOWN, MOVE FORWARD & RIG UP	8 HRS

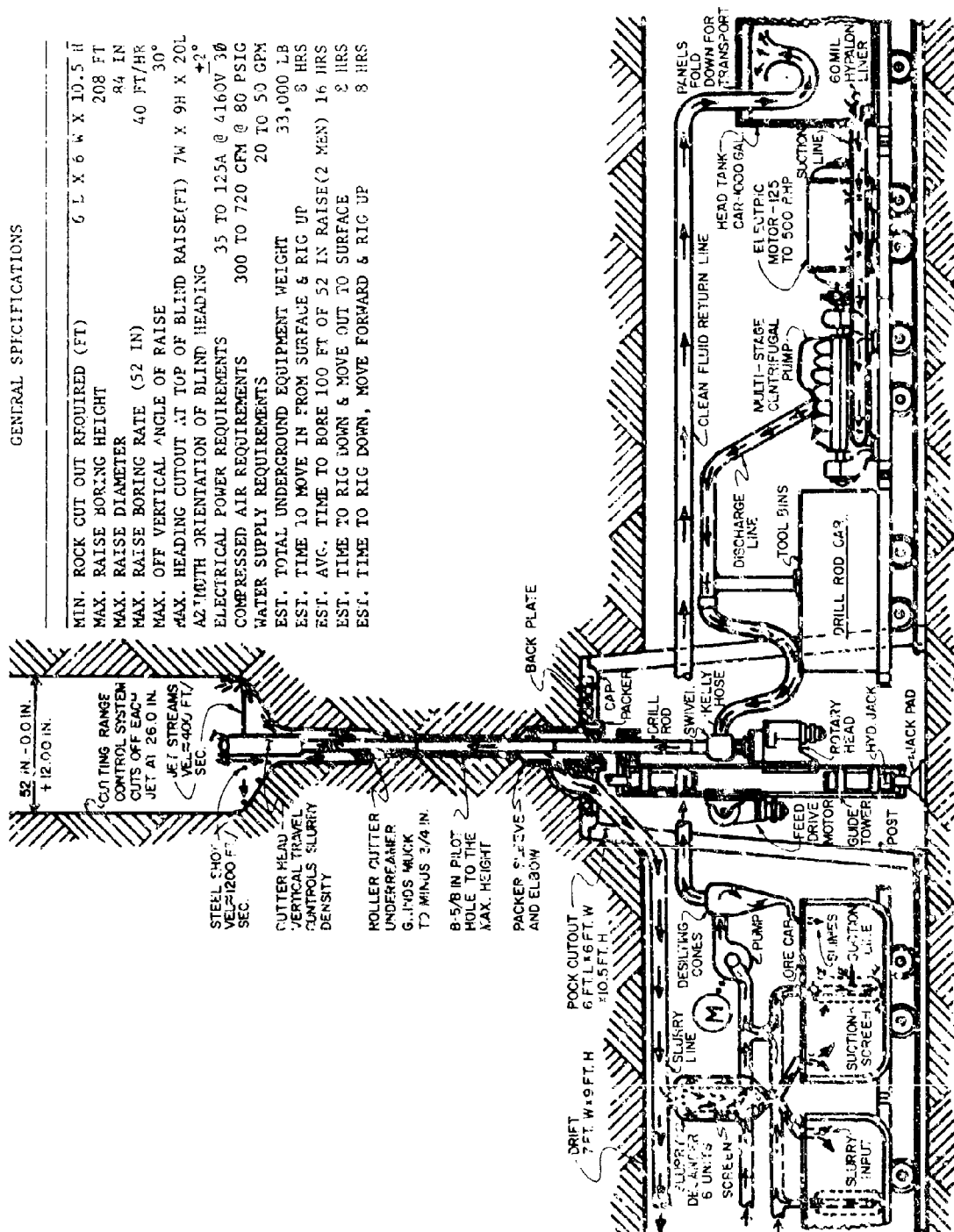


FIGURE 19 HYDRO-JET RAISE BORING SYSTEM

ROCK IS BROKEN FROM THE DRIFT FACE BY IMPINGEMENT WITH HIGH VELOCITY STEEL SHOT AND JET STREAMS OF WATER. CUTTINGS AND SHOT ARE WASHED DOWN TO THE ROLLER BIT, CRUSHED TO - 3/4 IN. AND JET PUMPED BACK TO SLURRY HANDLING SYSTEM. STEEL SHOT IS REMOVED FROM SLURRY LINE THRU THE HYDRAULIC CLASSIFIER: WASHED, SCREENED, & RECIRCULATED THRU THE STEEL SHOT NOZZLE. THICKENED SLURRY FROM THE 6 DESANDER UNITS IS LOADED DIRECTLY INTO THE 12 ORF CARS. SURPLUS WATER FROM THE ORE CARS & DESANDER UNITS IS PUMPED THRU THE DESILTING CONES INTO THE HEAD TANK CAR FOR DE-AERATION AND RECIRCULATION.

#### GENERAL SPECIFICATIONS

MIN. DRIFT FACE (FT)	7 W X 9 H
MAX. DRIFTING RATE (2 MEN)	8 FT/HR
MAX. SHOT FLOW RATE	100/SEC @ 1200 FT/SEC
MAX. FLUID FLOW RATE	600 GPM @ 1000 PSI
ELEC. PWR. REQ'D.	35 TO 125A @ 4160V 3Ø
COMPRESSED AIR REQ'D.	300 TO 600 CFM @ 80 PSIG
WATER SUPPLY REQ'D.	20 TO 50 GPM
MAX. CAR DIM. DISMANTLED (FT)	7 L X 4.5 W X 4.5 H

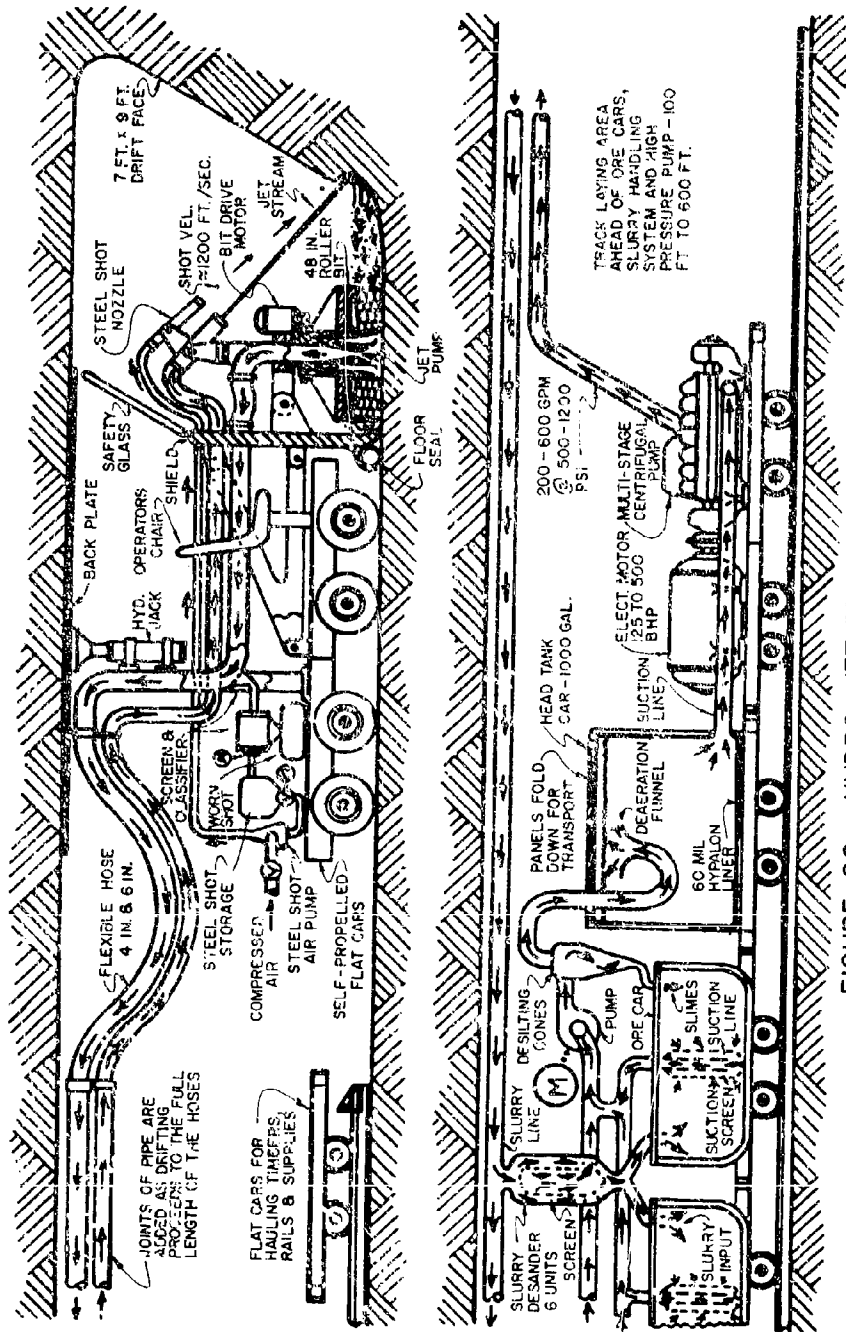


FIGURE 20. HYDRO-JET DRIFTING SYSTEM

#### APPENDIX IV

##### DOWELL HYDRAULIC UNDERREAMER

This appendix includes details of the Dowell hydraulic underreaming process as presented in a report from Mr. W. M. Zingg of Dowell Division of The Dow Chemical Company, Tulsa, Oklahoma.

## FORMING UNDERGROUND CAVITIES IN UNCEMENTED SOILS BY HYDRAULIC UNDERREAMING

### Introduction

Underground storage cavities are principally constructed at present by manual methods. Considerable interest has been expressed in recent years in creating cavities by working through a small bore hole. Here the methods are a choice either of mechanical underreamers or of high pressure jetting.

A. B. Fly in his patents teaches a jetting system which has been tested under actual conditions. In addition there are many other schemes which have been disclosed. Most of the latter represent ideas but have given little recognition to the practical solution of problems existing in such a process. These include features such as optimum pressures, velocity, overburden pressures, metallurgy and actual working designs.

### General Plan

The system (Figure 1)<sup>1</sup> consists of a rotary drilling rig, a dual string of tubing inside casing, and surface equipment to provide pumping of fluid. In its application, 10-3/4-inch surface pipe would be set to the top of the cavity. The drilling string would be lowered into the surface pipe and jetting started at the top of the desired cavity. The drill bit would run ahead to stabilize the drilling string as well as to grind up large formation lumps to a particle size permitting them to be removed by reverse circulation. All formation material removed would be forced to flow through the bit.

### Surface Equipment

While a triplex pump might be used, it is more desirable to consider using a high performance centrifugal pump from the standpoint of obtaining steady state conditions of the drill string. The type we propose would deliver 1000 gpm at 1000 psi. This would result in a velocity of approximately 40 ft/sec in 3 1/2 inch tubing. Thus, at shallow depths we do not see the need for an air lift system. However, at greater depths and if larger diameters were desired, probably an air system to keep the water scavenged to the bottom of the hole would be required in order that the jetting streams not be submerged to destroy their impact energy.

The rotary rig and drilling head assembly would largely be adapted from standard swivels, rotary drilling heads, etc.

A suitable mud tank is going to be a necessity in order to separate the cuttings and water.

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<sup>1</sup>This figure number refers to Figure 21.



Bore Hole Design (Figure 2)<sup>1</sup>

Research has yielded a jet design (Patent 3,348,616) assembly which permits utilizing optimum approach factors along with a nozzle configuration that controls flaring and orifice inversion at distances up to 20 feet. It also permits, within limits, placing the nozzle closer to the working surface. We would suggest the downhole tool design be patterned somewhat along these principles. However to make this possible it is almost mandatory that the surface pipe be 10-3/4, even larger (13-3/8) would be better but we think there is a good chance the design can be accomplished to run through 10-3/4 pipe.

The stinger below the jetting tool may be slotted to permit direct return of clean fluid. However, the size and number of slots must be carefully calculated to retain sufficient velocity through the bit passages.

Little control is visualized in the shape of the cavity. Much will depend upon the homogeneity of the soil structure. At a steady rate of traverse, certainly the diameter will not be uniform. Back-tracking might be necessary to remove the harder stratas. Dowell Sonar Caliper survey can be used to verify the size and shape of the cavity at any time during the operation when the drill string is out of the hole.

Time Required

Circulating fluids can easily transport one pound of sediment per gallon. For estimating purposes and if we assume the formation is going to disintegrate at this rate, then 1000 lbs of material is going to be removed in one minute, or approximately 2.3 minutes per cubic yard. A 12 ft x 48 ft chamber contains 200 cu yds. The actual pumping time to remove this volume of material is 8 hours.

Whether this rate can actually be achieved is perhaps another matter and would be subject to confirmation by actual operations. However this gives us some idea as to the time required. Actually, this pumping time would be interrupted by pulling the drill pipe, maintenance operations, surveys, etc. so that the overall time involved might more realistically cover two to three days of work.



---

<sup>1</sup>This figure number refers to Figure 22.

TABLE X  
ESTIMATED COST  
HYDRAULIC UNDERREAMING  
One - 12 ft x 48 ft Cavity

WMZ  
1/11/71

## I. Drilling Contractor Cost Items

Cost of rig, mud tank, water supply and disposal - not included

## 1. Well Equipment

7-inch casing swivel	\$ 400.00	
7-inch casing rotating head		
\$30.00/day w/10 day minimum	300.00	
7-inch stripper rubber	250.00	
3-1/2-inch tubing swivel	<u>1200.00</u>	
		\$2150.00

## 2. Casing and Tubing

90 ft - 7 inch x 17 lb H-40 casing	190.00	
30 ft - 10-3/4 inch x 32.75 lb H-40 casing	185.00	
90 ft - 3-1/2 inch J55 tubing	<u>120.00</u>	
		495.00

## II. Dowell Cost Items

## 1. Mobilization

Mileage	400.00	
Conditioning centrifugal pump	1000.00	
Construction of jetting tool	650.00	
Construction of stinger	500.00	
Modification of contractors' mud tank	<u>400.00</u>	
		2950.00

## 2. Service (3 days)

Personnel (3 operators)	915.00	
Allison powered 1000 HP centrifugal pump	1440.00	
Transportation	350.00	
Per Diem	180.00	
Consulting fee including per diem	<u>600.00</u>	
		3485.00

Total

\$9080.00

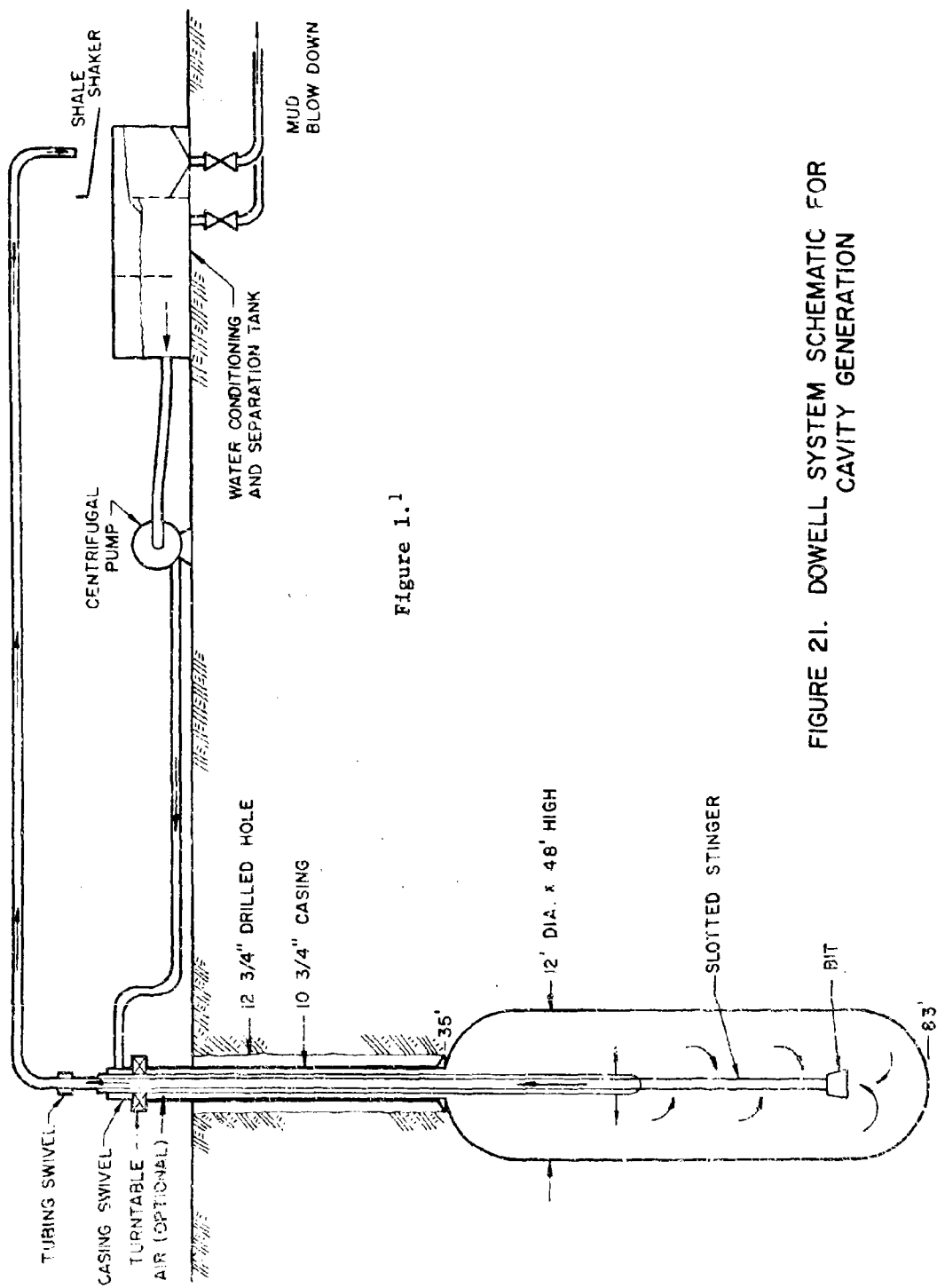


Figure 1.<sup>1</sup>

FIGURE 21. DOWELL SYSTEM SCHEMATIC FOR CAVITY GENERATION

<sup>1</sup>This figure number refers to Appendix IV text.

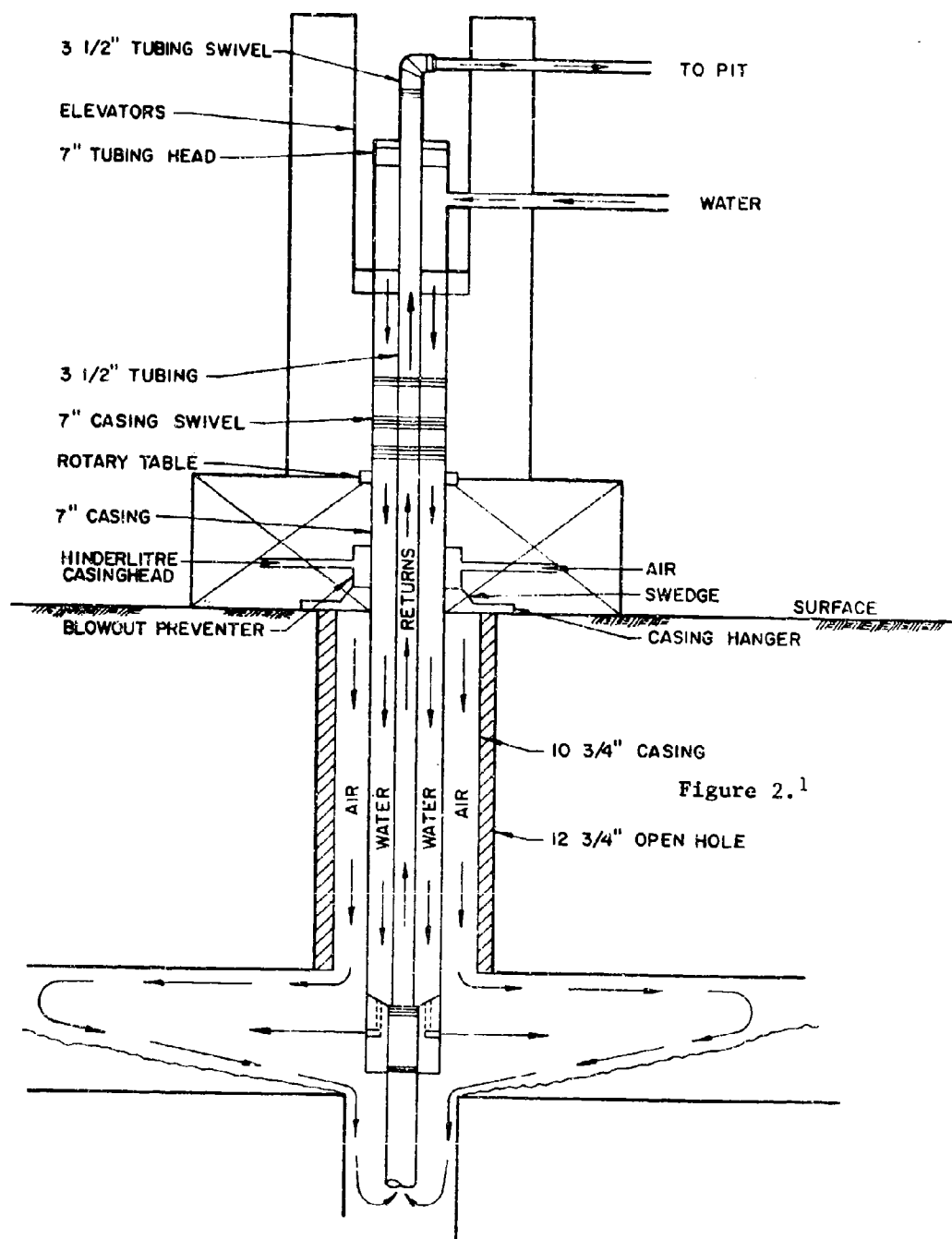


FIGURE 22. SCHEMATIC OF DOWELL HYDRAULIC UNDERREAMER

<sup>1</sup>This figure number refers to Appendix IV text.

# United States Patent Office

3,348,616  
Patented  
Oct. 24, 1967

3,348,616

## JETTING DEVICE

Warren M. Zingg, Tulsa, Oklahoma, assignor to The Dow Chemical Company,  
Midland, Michigan, a corporation of Delaware

Filed June 11, 1965, Ser. No. 463,289

6 Claims. (Cl. 166--223)

This invention relates to jetting tools of the type used in oil or gas wells, and particularly to a jetting tool which is adapted for use in so-called open hole jetting service.

Jetting tools for use in down-hole well treating or servicing use are well known in the art. An example of such a device is shown and claimed in U. S. Patent No. 3,066,735 issued December 4, 1962, to Warren M. Zingg.

Most of the prior art jetting tools have been made for use in cased wells or for use where the surface against which the abrasive or other jet stream is directed is a short distance, e.g., less than 6 inches, from the body of the tool. Because the tool is usually used where the bore hole is liquid filled at the point of use, it can be appreciated that the distance between the jet nozzles and the surface to be worked on should be as small as practicable if really effective use of the jets is to be achieved.

However, since the jetting tool must be lowered through well casing, it can be appreciated that the overall diameter of the tool must be small (7" O. D. casing is commonly used).

Accordingly, a principal object of this invention is to provide an improved jetting tool for use in well treating service.

Another object of this invention is to provide an improved jetting tool which is adapted to be lowered into a well bore through well casing but is adapted for use against a surface which is substantially further distance from the tool than is the wall of the casing.

A further object of this invention is to provide an improved jetting tool which is adapted to be used to jet surfaces of a large diameter cavity in a bore hole but may be raised from and lowered to the bore hole cavity through a small diameter casing.

In accordance with this invention, there is provided a well jetting tool comprising an elongated rigid body member having tubular means extending along and mechanically coupled thereto. Jetting assemblies, adapted to swivel during use, are coupled to the tubular means at spaced apart intervals along the body member. The jetting assemblies include a swivel head and elongated jet tubes having jet nozzles at their outer extremities. Means are provided for controlling the degree of swiveling of the jetting assemblies.

The invention, as well as additional objects and advantages thereof, will best be understood when the following detailed description is read in connection with the accompanying drawing, in which:

FIG. 1<sup>1</sup> is a side elevational view, in section, of jetting apparatus in accordance with this invention;

FIG. 2<sup>1</sup> is a side elevational view taken 90 degrees from the view of FIG. 1<sup>1</sup>;

FIG. 3<sup>1</sup> is a sectional view of a swivel element used in a jet assembly of FIG. 1<sup>1</sup>; and

FIG. 4<sup>1</sup> is a sectional view taken along the line 4--4 of FIG. 3<sup>1</sup>.

Referring to the drawings, there is shown a jetting tool, indicated generally by the numeral 10, comprising an elongated body member 12 of solid bar stock having coupling elements 14, 16 at each end.

A fluid flow line, indicated generally by the numeral 18, extends from near the coupling element 14 towards the lower end coupling element 16 of the body member 12. The flow line 18 is "threaded" back and forth through the bar-like body member in a plurality of loops. The flow line 18 is welded or otherwise mechanically coupled to the body member 12 each time it passes through the body member, as at 20, 22, 24, 26, for example.

A plurality of jet head assemblies, indicated generally by the numeral 28, are coupled, by means of tubes 30, 32, 34, 36 to the flow line 18. Each of the tubes 30, 32, 34, 36 fixedly secured, as by welds, for example, to the body member 18.

Referring now to FIGS. 3<sup>1</sup> and 4<sup>1</sup>, as well as to FIGS. 1<sup>1</sup> and 2<sup>1</sup>, it may be seen that the swivel member 38 of the jet head assembly 28 includes a bolt-like element 40 having a head 42, and a cylindrical part 44 having threads 46 at its end which has reduced diameter. A bore 48 extends longitudinally from the end 50 of the element towards the head 42. A cross-bore 52 extends through the cylindrical part 44 of the member 38.

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<sup>1</sup>These figure numbers refer to U. S. Patent No. 3,348,616 drawings, Appendix IV.

A pair of grooves 54, 56 extend around the periphery of the cylindrical part 44, one groove being on each side of the bore 52. An "O" ring seal 58, 60 is disposed in each groove 54, 56, respectively.

A cylindrical element 62 whose thickness is less than its diameter and whose diameter is substantially larger than the diameter of the cylindrical part 44, has an axially extending bore 64 completely through it. A transverse bore 66, having threads 68 at its outer end, extends from the periphery of the element 62 to the bore 64. The bore 66 is of smaller diameter than the distance between the grooves 54, 56.

When the element 62 is assembled over the cylindrical part 44 of the element 38, the O-ring seals 58, 60 bear against the wall of the bore 64 and prevent leakage of fluid along the bore 64. Communication for fluid flow is provided through the bores 48, 52, and 66.

As may be seen more clearly in FIGS. 1<sup>1</sup> and 2<sup>1</sup>, an "elbow" type flow element 70 is coupled to the threaded end 68 of the bore 66, with another elbow type coupling element 72 being coupled to the output of the element 70. A flexible hose 74 having a jetting nozzle 76 coupled to one end, has its other end coupled to the output of the element 72.

The hose 74, nozzle 76, elements 70 and 72, and the element 62 are so aligned that flow through them tends to cause movement of the mentioned elements along a single plane.

Stop means, in the form of a protuberance 78 extending from the body member 12 in the path of movement of the element 70, is provided to prevent excessive rotation of the jetting assembly 38 as material is flowed therethrough.

In operation, the jetting tool 10 is coupled by means of coupling 14 to a string of tubing (not shown) and is lowered down a bore hole through casing until the tool 10 is beyond the casing and is adjacent to an enlarged part of the bore hole, such as where the bore hole had previously been shot with nitro glycerin, for example. If desired, additional tubing (not shown) may be coupled, as at 16, below the tool 10.

The string of tubing (not shown) which is attached to coupling 14 communicates with flow line 18 by a passageway through coupling element 19 which joins coupling 14 and flow line 18. A suitable pumping means (not shown) is attached at the upper end of the string of tubing for forcing fluids and/or fluids plus abrasive material down the flow line 18 as is well known in the art.

When the tool is in position, fluid is forced through the flow line 18 and through the jetting assemblies 38, causing the assemblies to rotate until stopped by the pins or protuberances 78. The pins 78 stop the assemblies 38 when the nozzles 76 are directed horizontally or nearly perpendicularly with respect to the longitudinal axis of the body member 12.

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<sup>1</sup>These figure numbers refer to U. S. Patent No. 3,348,616 drawings, Appendix IV.

Actually, as illustrated, the pins 78 cause the nozzles 76 to be directed at an angle about 30 degrees less than perpendicular with respect to the body member 12.

Thus, as the jetting assemblies rotate, the nozzles are advanced towards the wall of the bore hole and the distance of the nozzles from the body member 12 may be greatly in excess of the radius of the casing.

When the jetting treatment is completed, the jetting assemblies are free to return to their "at rest" position parallel to the body member 12, thus permitting the jetting tool 10 to be withdrawn from the bore hole through the casing.

The swiveled jetting assembly is threadedly coupled to the flow line 18 through the tube 30, 32, 34, for example.

Flexible tubing 74 of different lengths may be used, the required length usually being determined after interpretation of a profile survey of the part of the bore hole to be jetted.

In practice, jet nozzles 76 having a 1/8 inch orifice are commonly used. Because such orifices are easily plugged, it is often wise to mount a filter screen just above the tool 10 to prevent plugging of the jet nozzles by scale from the tubing or similar particulated materials.

The swivel arrangement of the jetting assemblies causes the jetting assemblies to fold downwardly towards the body member 12 as the tool is raised into the casing in event the weight of the jet assembly does not cause this movement of its own accord.

Thus, this invention provides a simple, convenient to use means for jet cleaning and perforating of the walls of well bores where the wall surface is beyond the effective distance of ordinary jetting tools.

1. A jetting tool assembly comprising an elongated body member having coupling means at least at one end thereof, a flow line extending along said body member and mechanically coupled thereto at intervals along its length, said flow line having a coupling element adjacent to an end of said body member, a plurality of swiveled jetting assemblies, said jetting assemblies being mechanically coupled to said body member and fluid flow coupled to said flow line at spaced apart intervals along the length of said body member, said jetting assemblies each comprising a swivel head having an offset flow member coupled thereto and a jetting nozzle coupled to said offset flow member by a conduit.

2. A jetting tool assembly in accordance with claim 1, wherein stop means are provided for preventing excess movement of said swivel heads.

3. A jetting tool assembly in accordance with claim 1, wherein



said jetting assemblies are coupled to more than one side of said body member.

4. A jetting tool assembly in accordance with claim 1, wherein said flow line passes through said body member at spaced apart intervals along said body member.

5. A jetting tool assembly in accordance with claim 1, wherein said conduit and nozzle are detachably coupled to said offset flow member.

6. A jetting tool assembly comprising an elongated body member having coupling means at least at one end thereof, a flow line extending along said body member and mechanically coupled thereto at intervals along its length, said flow line having a coupling element adjacent to an end of said body member, at least one swiveled jetting assembly, said jetting assembly being mechanically coupled to said body member and fluid flow coupled to said flow line, said jetting assembly comprising a swivel head having an offset flow member coupled there to and a jetting nozzle coupled to said offset flow member by a conduit.

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CHARLES E. O'CONNELL, Primary Examiner.

JAMES A. LEPPINK, Examiner.

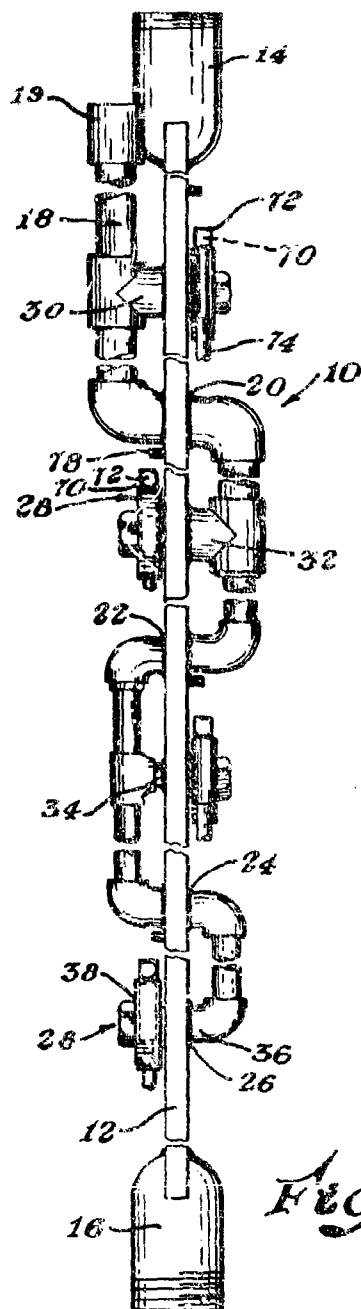
Oct. 24, 1967

W. M. ZINGG  
JETTING DEVICE

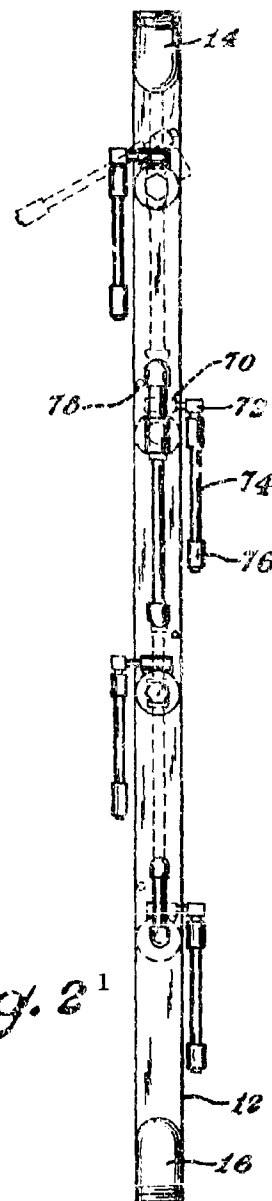
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2 Sheets-Sheet 1



*Fig. 1*<sup>1</sup>



*Fig. 2*<sup>1</sup>

INVENTOR  
Warren M. Zingg

BY *Earl D. Ayers*

AGENT

FIGURE 23. JETTING DEVICE

<sup>1</sup>These figure numbers refer to U. S. Patent No. 3,348,616 text, Appendix IV.

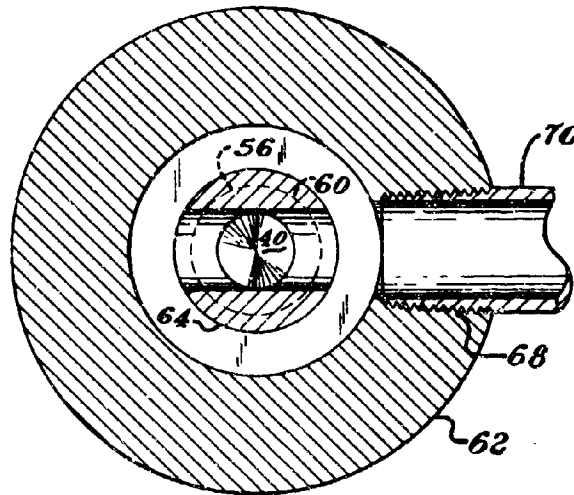
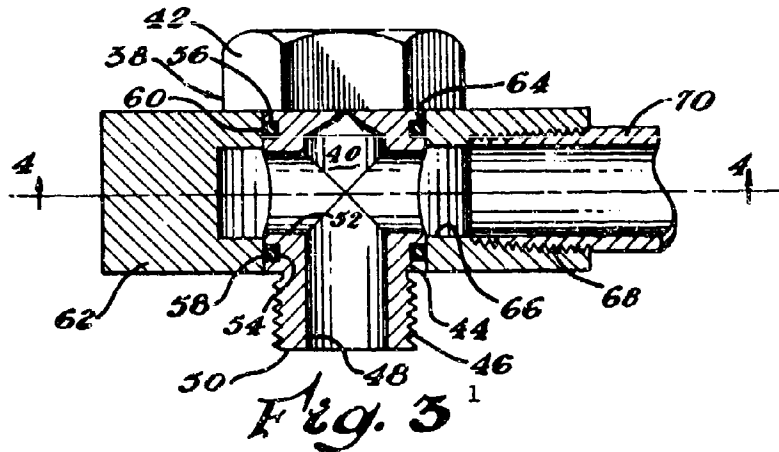
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Filed June 11, 1965

W. M. ZINGG  
JETTING DEVICE

2 Sheets-Sheet 2



INVENTOR  
Warren M. Zingg  
BY *Earl D. Ayers*  
AGENT

FIGURE 24. JETTING DEVICE DETAILS

<sup>1</sup>These figure numbers refer to U. S. Patent No. 3,348,616 Text, Appendix IV.

## APPENDIX V

### CAVITY CONFIGURATION

The ideal cavity configuration would be one which is economical to create in any type of material, and structurally stable regardless of the stress field or the competency of the surrounding strata. It would also be susceptible to exact design formulas based on mechanical properties as determined from laboratory tests.

Unfortunately, the study of rock and soil mechanics is not an exact science and the classification of rock or soil as a structural material in which underground openings can be constructed is not a simple problem. An acceptable approach to classifying rock is to consider the combination of geological and mechanical rock properties that will permit the construction of a specified type of underground structure. For example, Obert, Duvall and Merrill (Ref. 26) defined competent rock as that rock which because of its mechanical and geological characteristics is capable of sustaining underground openings without the aid of any structural support except pillars and walls left during mining.

Relationships have been developed between stress, strain and deformation for an ideally elastic, isotropic and homogeneous continuous medium. These relationships can be used to determine the state of stress, strain or deformation in bodies of different shapes subjected to various applied loads and sets of boundary conditions. Only those body shapes that can be expressed by a simple mathematical equation are amenable to solution. The assumptions regarding the body material may be modified to include ideally viscous, or ideally viscoelastic materials.

However, in structures made of real materials, the ideal property requirement is never satisfied since no real rock is strictly linear-elastic, elastoplastic, purely viscous, or viscoelastic. Some large bodies of rock may approximate an elastic material to the degree that engineering requirements are satisfied; however, in-situ rock generally contains fractures, joints, faults and inhomogeneities to the degree that significant deviation from ideal conditions occurs.

The magnitude and direction of the stress in the rock surrounding an underground opening depends on the stress-field, that is, the state of stress in the rock before the opening was created. A gravitational stress-field might be assumed, i.e., a stress-field due to the weight of the overlying cover. However, to completely specify a gravitational stress field, it must be assumed that the rock is linear-elastic, isotropic, and homogeneous; that the lateral constraint is complete; and that there are no stresses of tectonic origin such as those accompanying folding, shrinkage, or other distortions of the earth crust. The gravitational stress field can be significantly affected by these tectonic stresses together with the effects of inelasticity, inhomogeneity, and anisotropy.

Because of the limitations imposed by mathematical complexity, and because of the error introduced by assuming ideal rock properties and a known stress-field, theoretical methods in themselves generally will not provide a satisfactory answer to specific structure problems. To some degree theoretical results may be supplemented or modified by experience gained from observation in underground workings. When empirical methods, i.e., measurement of rock properties and structural stresses and strains in laboratory models, are used to supplement or modify theory,

the product is a rational basis for analyzing rock structure problems.

#### 1. STATE OF STRESS AROUND AN UNDERGROUND CAVITY

The rock at any depth below the ground surface at a given site may be considered to be in an initial state of equilibrium. The excavation of an opening will produce changes in the stress system, and in turn brings about elastic and inelastic displacements and a redistribution of stresses in the material surrounding the opening as a new condition of equilibrium is established. The factors that determine the new stress pattern and the behavior of the rock surrounding the opening includes:

1. The initial state of stress in the rock mass.
2. Shape of the opening.
3. Size of the opening.
4. Elastic and inelastic properties of the rock.
5. The geologic discontinuities of the mass.

At the present state of knowledge it is not possible to evaluate quantitatively all these factors. However, the influence of the various factors on the overall stability of the opening is discussed.

##### a. INITIAL STATE OF STRESS

The initial state of stress refers to the relationship between the vertical stresses caused by the weight of the overlying rock at any given depth and the horizontal stresses acting at the same point. The ratio of the horizontal stress to the vertical stress will be designated by the coefficient  $m$ . Most investigators of the problem of stress distribution around a hole in an elastic medium have assumed the initial state of stress to fit one of the following conditions:

- (1) A condition of no lateral restraint, or  $m = 0$ . May occur at shallow depths, and/or near a vertical free surface.

- (2) A condition of lateral restraint in which  $m$  ranges from about 0.25 to 1, depending upon the value of Poisson's ratio. May occur over a wide range of depths.
- (3) A hydrostatic condition of equal all around pressure where  $m = 1.0$ . May occur at great depth or in semi-viscous or plastic rocks. (Recent work by Terzaghi and Richert indicate another condition might exist where  $m > 1$ ) (Ref: 29).

Both analytical and model studies have shown that the stress distribution around an opening of given shape varies greatly depending on which of the above initial stress conditions one assumes. Unfortunately, it is not possible to compute, by means of theory, the value of  $m$  for a given site.

b. CONDITION OF NO LATERAL RESTRAINT: The initial stress condition in which  $m$  is equal to zero may be approximated at a shallow depth or in a formation which is traversed by numerous open vertical joints.

c. CONDITION OF LATERAL RESTRAINT: In a perfect homogeneous elastic material it is possible to compute the value of  $m$ ,

$$m = \frac{\mu}{1-\mu}$$

where  $\mu$  is Poisson's ratio. Normally, Poisson's ratio for most rocks has been found to range from 0.2 to 0.5, leading to  $m$  values of 0.25 to 1.0. The equation does not hold for rock masses which are not homogeneous but contain many discontinuities.

d. HYDROSTATIC CONDITION: In the hydrostatic state, the stress at a given point is considered to be equal in all directions, wherein  $m = 1$ . From the equation it is evident that for a material with Poisson's ratio of 0.5,  $m = 1$ . The only common rock for which Poisson's ratio has been found to be 0.5 is rock salt. It may be postulated therefore that the salt in domes and salt beds approximates the hydrostatic condition.

## 2. FIELD MEASUREMENT OF INITIAL STATE OF STRESS

It has been pointed out that the value of  $m$ , the ratio of the horizontal stress to the vertical stress, greatly influences the stress pattern which develops around an excavated cavity. Further, the magnitude of  $m$  may vary from 0 to greater than 3. There is no analytical or geological method by which to evaluate  $m$  for a given site, but in recent years progress has been made in the determination by field measurements. Moye (Ref. 28), Terzaghi and Richert (Ref. 29), Olsen (Ref. 30). These methods represent the only reasonable approach to determination of the initial state of stress.

## 3. SHAPE OF OPENING

The magnitude and distribution of stress around a cavity depends to great extent on the initial stress and shape of the cavity. For a given  $m$  value there is an optimum shape which produces the most favorable stress distribution. This relationship may be investigated mathematically in accordance with the theory of elasticity for a homogeneous elastic medium.

The stress distribution around various shaped openings has been determined theoretically for various major-to-minor axis ratios and for various ratios of applied loads. In theory, the stress distributions are independent of the size of opening and the elastic constant of the material. Contrary to theory, however, practical experience in underground excavation has shown that difficulties in maintaining stable openings increase directly with the size of the opening. This may be explained by the discontinuities which occur in all rock masses.

Sandowsky and Sternberg (Ref. 31), Edwards (Ref. 33), and Neuber (Ref. 34) have developed mathematical solutions of the elasticity problem.



Terzaghi and Richert (Ref. 29) determined theoretically the stress distribution about a triaxial ellipsoidal cavity in an infinite medium under triaxially-applied load. The results indicate the maximum-stress concentration around an elliptical cavity are always less than the maximum-stress concentrations around tunnels having the same cross-sectional shape. This has been verified by studies of Langharr and Baresi (Ref. 27) and Obert and Duvall (Ref. 32) on other cavity configurations. Thus, for engineering purposes, the maximum-stress concentration for single isolated openings can be estimated safely by determining the maximum-stress concentration around any two-dimensional opening where the cross-sectional shape is the same as the cross-section of the three dimensional opening.

Figure 25 shows the boundary stress distribution curves for elliptical holes in a biaxial stress field with various width to height ratios and various ratios of applied normal stresses. Figure 26 provides similar information for ovaloidal holes; Figure 27 for rectangular holes; and Figure 28 for a circular hole. Symbols used in the Figures are as follows:

$H_o$  = height of cavity

$W_o$  = width of cavity

$$m = \frac{S_h}{S_v} = \frac{\mu}{1-\mu}$$

$$S_h = m S_v$$

$$S_v = \gamma h$$

$\gamma$  = unit weight of overlying rock

$h'$  = vertical distance from ground surface to opening.

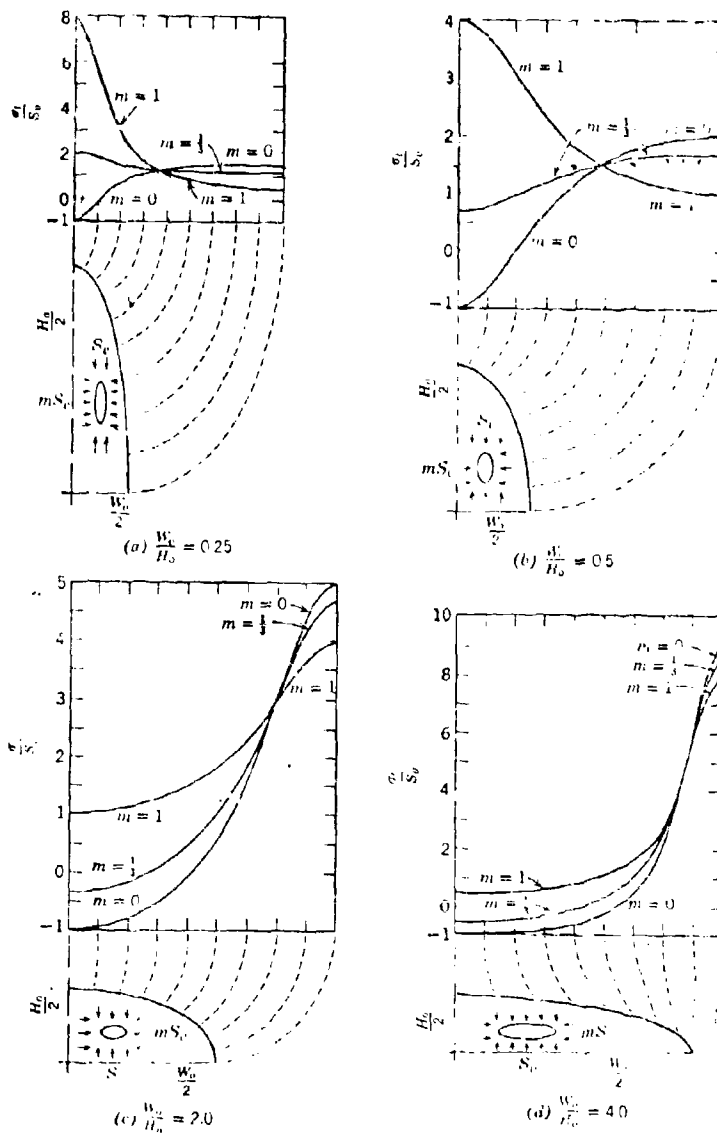


Figure 25. Boundary-Stress Concentration for Elliptical Holes in a Biaxial Stress Field

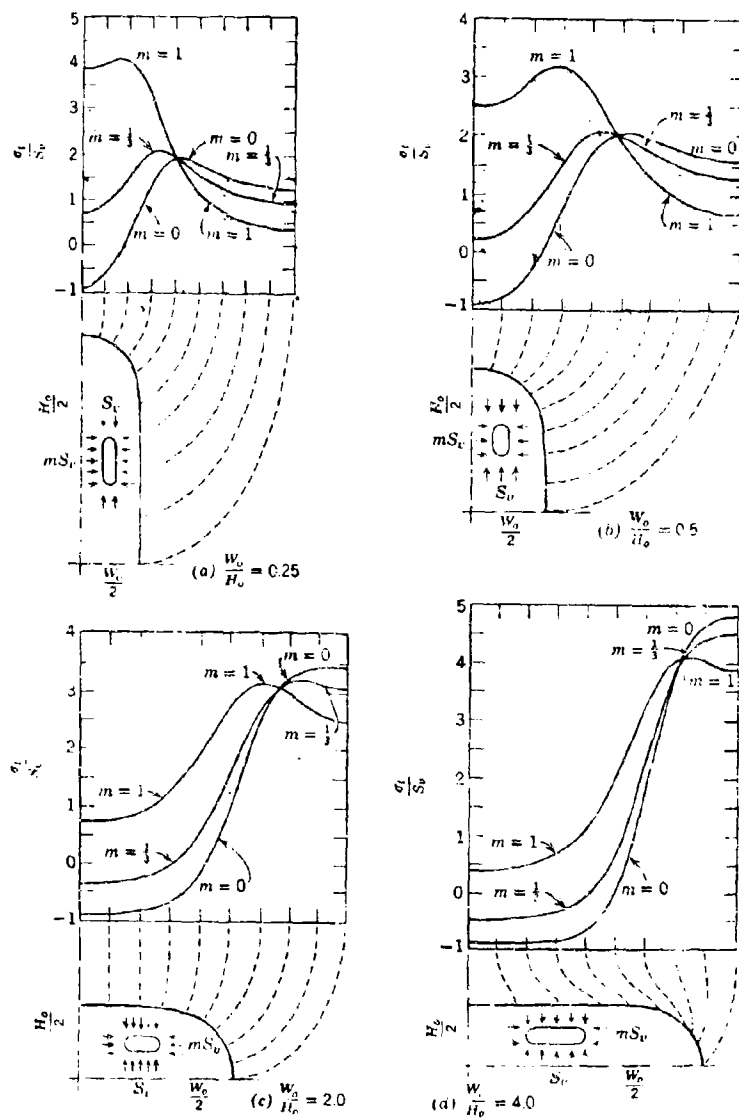


Figure 26. Boundary-Stress Concentration for Ovaloidal Holes in a Biaxial Stress Field

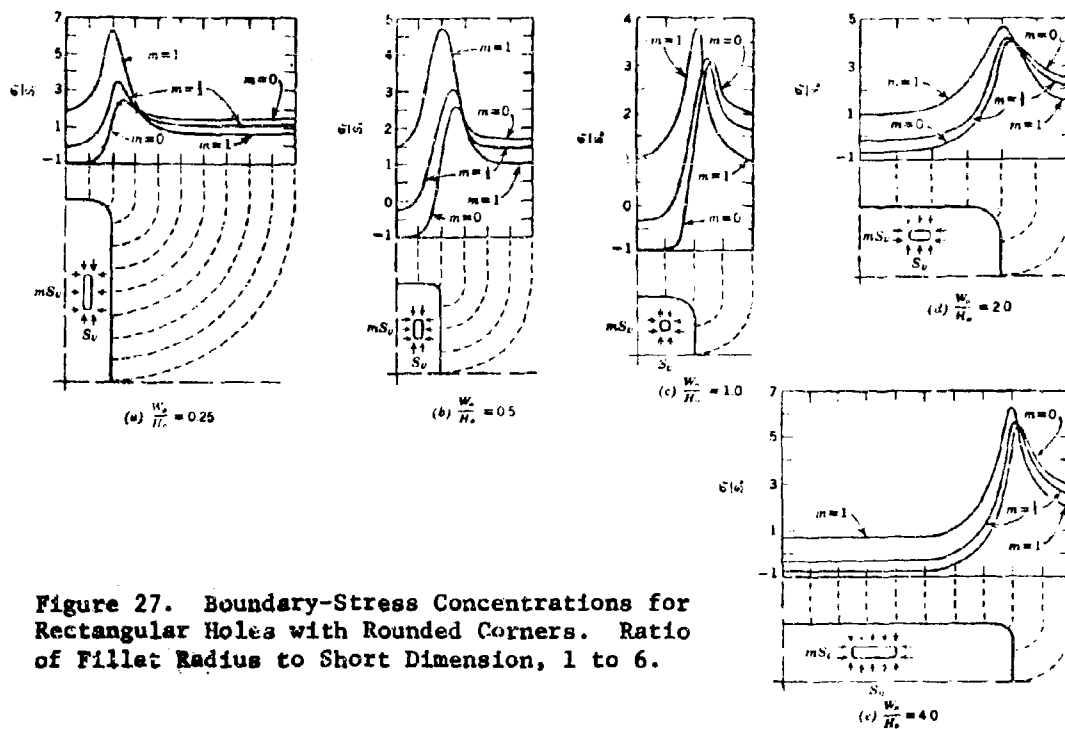


Figure 27. Boundary-Stress Concentrations for Rectangular Holes with Rounded Corners. Ratio of Fillet Radius to Short Dimension, 1 to 6.

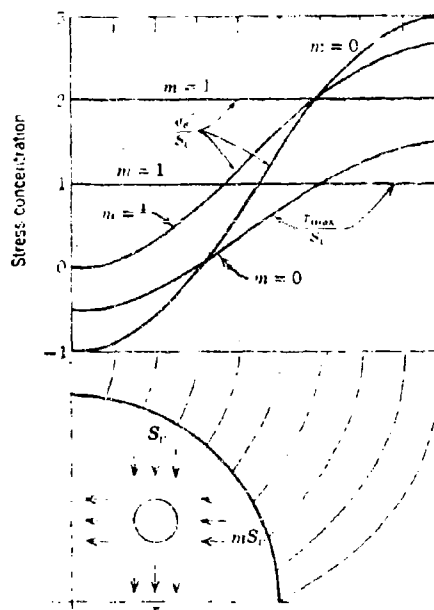


Figure 28. Boundary-Stress Concentrations for a Circular Hole in a Biaxial Stress Field

A positive stress concentration means that the stress at a certain point has the same sign as the applied stress. A negative stress concentration means that the stress at a point has the opposite sign and the material is in tension. The maximum positive and the minimum negative stress-concentrations are called critical stress concentrations. The optimum shape of opening is the one that simultaneously gives the smallest values of the stress concentration factors, and where there is an absence of tensile stress (no negative value of the stress concentration factor).

#### 4. DESIGN CONCLUSIONS (REF. 32)

Based on a two-dimensional opening with a height and width,  $H_0$  and  $W_0$ , in an elastic, isotropic, homogeneous rock and subjected to applied vertical ( $S_v$ ) and horizontal stresses ( $S_h = m S_v$ ), with  $0 < m < 1$ , it follows that:

a. For a uniaxial stress field ( $S_h = 0$ ) or a biaxial stress field ( $S_h = m S_v$ ).

(1) The stress distribution on the boundary is dependent upon the shape, but not the size of the opening. Hence, critical stresses are dependent on the opening shape but not on the opening size.

(2) The boundary and axial stress distribution is independent of the elastic constants of the rock. Hence, critical stresses are independent of the elastic property of the rock.

(3) Critical stress concentrations increase as the radius of curvature of the boundary decreases (except for tensile critical stress concentrations in a uniaxial stress field). Therefore, openings with sharp corners should be avoided.

(4) The tangential stress concentration on the extension of the horizontal axes through an opening of any shape is a maximum at the boundary and decreases rapidly with distance from the boundary. Moreover, the greater the boundary stress concentrations, the more rapidly the stress distribution curve will decrease with distance from the boundary. For example, at a distance of one diameter along the horizontal axis from the boundary of a circular opening in a biaxial stress field ( $m = 1/3$ ) the tangential stress is less than 5% greater than the applied vertical stress. Consequently the stress distribution around an opening is not appreciably influenced by the presence of other openings or surfaces if it is separated from them by a distance equal to the length of the axis through the opening. Thus, if this condition is satisfied, the opening is single.

(b) For a uniaxial stress field:

(1) If  $(W_o/H_o) > 1$ , ovaloids or rectangles with rounded corners will give smaller critical compressive stress concentrations at ends of the horizontal axis than ellipses. If  $(W_o/H_o) < 1$ , an ellipse is the best shape.

(2) If the vertical applied stress is parallel to the height of an inclined or canted opening, a critical tensile stress concentration of -1 will develop at the end of the vertical axis. Since the tensile strength of rock is small this tension may be significant.

(c) For a biaxial stress field:

(1) An elliptical opening with its major axis parallel to the vertical applied stress will develop smaller critical compression stress concentration than any other opening shape. For a given stress field, if  $(W_o/H_o) = (S_h/S_v)$  then the critical stress at all points on the boundary

will be compressive, constant and minimum. Thus an ellipse with the proper ratio of axes is the ideal opening for a stress field (other than uniaxial).

(2) If  $(W_o/H_o) > 1$ , ovaloidal or rectangular openings will induce lower critical compressive stress concentrations than elliptical openings.

(3) The tensile stress at the ends of the vertical axis of all openings in a uniaxial stress field ( $m = 0$ ) will decrease and become compressive as  $m$  increases. For  $(W_o/H_o) \leq 1$ , this transition from tension to compression occurs for  $m = 1/3$ .

(d) For a hydrostatic stress field:

(1) The preferred opening is a circle. When a height-to-width ratio smaller or greater than unity is desired, an ovaloid will induce lower critical stresses than either the ellipse or rectangle.

(2) No tensile stresses develop for any shape of opening. The summary chart, Figure 29 indicates the preferred cavity configurations for the shapes and ratio of stresses studied.

It must be recognized that the ideal shape for the cavity, from the viewpoint of structural integrity, may not be the most feasible or economical shape to create due to equipment limitations. The configuration preference may be approximated by utilization of the shape selection for underground cavities (Figure 29). The following Table XI indicates the assumed inplane ratio of stresses ( $\frac{S_h}{S_v} = m$ ) for various soils at depths of 25 to 150 feet.

TABLE XI

RATIO OF HORIZONTAL TO VERTICAL STRESSES FOR VARIOUS SOILS

Soil Consistency	Ratio of Forces, $m$
Cohesive Soils	
Very soft to soft	1.0
Medium or plastic	0.5
Stiff to hard	0.25
Noncohesive Soils	
Very loose	1.0
Firm	0.5
Dense to very dense	0.25




























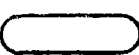

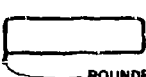


m	SELECTION				
	BEST	SECOND	THIRD	FOURTH	FIFTH
0	ELLIPSOIDAL $W_0/H_0 = 1/4$ 	ELLIPSOIDAL $W_0/H_0 = 1/2$ 	OVALOIDAL $W_0/H_0 = 1/4$ 	OVALOIDAL $W_0/H_0 = 1/2$ 	SPHERE $W_0/H_0 = 1$ 
0.25	ELLIPSOIDAL $W_0/H_0 = 1/4$ 	OVALOIDAL $W_0/H_0 = 1/4$ 	ELLIPSOIDAL $W_0/H_0 = 1/2$ 	OVALOIDAL $W_0/H_0 = 1/2$ 	SPHERE $W_0/H_0 = 1$ 
0.33	ELLIPSOIDAL $W_0/H_0 = 1/3$ 	ELLIPSOIDAL $W_0/H_0 = 1/4$ 	OVALOIDAL $W_0/H_0 = 1/4$ 	ELLIPSOIDAL $W_0/H_0 = 1/2$ 	OVALOIDAL $W_0/H_0 = 1/2$ 
0.50	ELLIPSOIDAL $W_0/H_0 = 1/2$ 	OVALOIDAL $W_0/H_0 = 1/2$ 	SPHERE $W_0/H_0 = 1$ 	ELLIPSOIDAL $W_0/H_0 = 1/4$ 	OVALOIDAL $W_0/H_0 = 1/4$ 
1.00	SPHERE $W_0/H_0 = 1$ 	OVALOIDAL $W_0/H_0 = 2$ 	OVALOIDAL $W_0/H_0 = 4$ 	ELLIPSOIDAL $W_0/H_0 = 2$ 	ELLIPSOIDAL $W_0/H_0 = 4$ 
> 1.00	OVALOIDAL $W_0/H_0 = 4$ 	OVALOIDAL $W_0/H_0 = 2$ 	RECTANGULAR $W_0/H_0 = 4$  ROUNDED CORNERS	RECTANGULAR $W_0/H_0 = 2$ 	ELLIPSOIDAL $W_0/H_0 = 4$ 
$m = S_h/S_v$ $W_0 = \text{Width of cavity}$ $H_0 = \text{Height of cavity}$					

FIGURE 29 SHAPE SELECTION FOR UNDERGROUND CAVITIES

## APPENDIX VI

### BORING LOGS AND LABORATORY TEST DATA SUMMARY

Four borings were drilled in order to determine the geologic formations at the proposed North Bryan Test Cavity Site. Engineering characteristics of the soil were obtained from laboratory tests performed on representative undisturbed soil samples. Logs of Borings and Summary of Laboratory Test Data are included in this appendix.

1

LOG OF BORING					
PROJECT Underground P.O.L. Storage Cavity			BORING NO WB-1		
CLIENT United States Air Force			LOCATION North Bryan Test Cavity Site		
DATE May 7, 1970		JOB NO 70-17		BORING TYPE Wash	
DRILLER C. Dean		SOIL ENGINEER A. Dean		GROUND ELEV	
Depth in Feet	Sample Type	Sample No	Penetrometer Reading, 1st	Blows / Foot	LEGEND
					<input type="checkbox"/> Core <input checked="" type="checkbox"/> Penetration Sample <input checked="" type="checkbox"/> No Recovery    J Jar <input type="checkbox"/> Static Water Table <input type="checkbox"/> Hydrostatic Water Table
DESCRIPTION OF STRATUM					
					Sandy silt topsoil 1'
5					Iron ore with clay layers 6'
10					Tan and gray clay 12'
15					Hard dark gray clay with thin silt seams (Partings)
20		1656	4+		-with trace of organic and tiny shells
25					
30					Sandstone - Siltstone 31'
35					Hard dark gray sandy clay with tiny shells
40		1657	4+		-with thin streaks of sandstone (Max. 2")
45					
50					-with 1" sandstone @ 48'
55					

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LOG OF BORING					
PROJECT		Underground P.O.L. Storage Cavity		BORING NO	WB-1
CLIENT		United States Air Force		LOCATION	North Bryan Test Cavity Site
DATE		May 7, 1970		JOB NO	70-17
DRILLER		C. Dean		BORING TYPE	Wash
		SOIL ENGINEER		A. Dean	
				GROUND ELEV	
LEGEND					
<input checked="" type="checkbox"/> - Core <input checked="" type="checkbox"/> - Penetration Sample <input checked="" type="checkbox"/> - No Recovery    J-Jar <input checked="" type="checkbox"/> - Static Water Table <input checked="" type="checkbox"/> - Hydrostatic Water Table					
DESCRIPTION OF STRATUM					
Depth in Feet	Sample Type & Sample No	Penetrometer Reading, lbf	Blows / Foot	Description	
57'				Hard dark gray sandy clay	
60'	1658	4+		Thin sandstone layers -becomes hard dark gray clay with thin sand seams (Partings)	
64'					
65'					
70'				Hard dark gray clay with thick sand layers (Max. 2'±)	
71'					
75'					
80'	1659	4+		Hard dark gray clay with silt seams (Partings)	
85'					
90'					
95'					
100'	1660	4+			
105'					
Bottom @ 101'					

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LOG OF BORING					
PROJECT Underground P.O.L. Storage Cavity			BORING NO WB-2		
CLIENT United States Air Force			LOCATION North Bryan Test Cavity Site		
DATE May 7, 1970		JOB NO 70-17		BORING TYPE Wash	
DRILLER C. Dean		SOIL ENGINEER A. Dean		GROUND ELEV	
LEGEND					
<div style="display: flex; justify-content: space-between;"> <span>■ - Core</span> <span>⊠ - Penetration Sample</span> <span>☐ - No Recovery J Jar</span> </div> <div style="display: flex; justify-content: space-between;"> <span>▽ - Static Water Table</span> <span>▼ - Hydrostatic Water Table</span> </div>					
DESCRIPTION OF STRATUM					
Depth in Feet	Sample Type & Sample No	Penetrometer Reading, 1st	Blows / Foot	Description	
5				Hard dark gray clay with silt partings	
10					
15					
20					
25					
30					
35					
40					
45					
50					
55				Hard sandy clay with trace of shells	
60					
65					
70					
75					
80					
85					
90					
95					
100					

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LOG OF BORING					
PROJECT Underground P.O.L. Storage Cavity			BORING NO WB-2		
CLIENT United States Air Force			LOCATION North Bryan Test Cavity Site		
DATE May 7, 1970		JOB NO 70-17		BORING TYPE Wash	
DRILLER C. Dean		SOIL ENGINEER A. Dean		GROUND ELEV	
LEGEND					
<div style="display: flex; justify-content: space-between;"> <span>■ - Core</span> <span>☒ - Penetration Sample</span> <span>☑ - No Recovery</span> <span>J-Jar</span> </div> <div style="display: flex; justify-content: space-between;"> <span>▽ Static Water Table</span> <span>▼ Hydrostatic Water Table</span> </div>					
DESCRIPTION OF STRATUM					
Depth in Feet	Sample Type & No	Penetration Reading, tsf	Blows / Foot	Description	
60				Hard sandy clay with trace of shells	
				60'	
				Sand	
				61'	
65				Hard gray clay	
70					
75					
				77'	
				Sand	
				77.2'	
80					
85				Hard gray clay	
90					
95					
100				Bottom @ 100'	

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LOG OF BORING					
PROJECT Underground P.O.L. Storage Cavity			BORING NO WB-3		
CLIENT United States Air Force			LOCATION North Bryan Test Cavity Site		
DATE May 8, 1970		JOB NO 70-17	BORING TYPE Wash		GROUND ELEV
DRILLER C. Dean		SOIL ENGINEER A. Dean			
LEGEND					
<input type="checkbox"/> - Core <input checked="" type="checkbox"/> - Penetration Sample <input type="checkbox"/> - No Recovery    J-Jar <input type="checkbox"/> - Static Water Table <input checked="" type="checkbox"/> - Hydrostatic Water Table					
DESCRIPTION OF STRATUM					
Depth in feet	Sample Type	Sample No	Penetrometer Reading, tsf	Blows / Foot	
5					Tan clay with iron ore
10					
15					
18.5					-becomes very stiff tan clay with sand pockets
20		1662	2.5		Dark gray sandy clay with shell
25					
30					
35					
40		1663	4+		-becomes hard dark gray clay with small shell
41					41'
41.7		1664		182 1"	Gray sandstone
41.7					41.7'
45					Hard dark gray clay with small shell
50					
55					

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LOG OF BORING					
PROJECT Underground P.O.L. Storage Cavity			BORING NO WB-3		
CLIENT United States Air Force			LOCATION North Bryan Test Cavity Site		
DATE May 8, 1970		JOB NO 70-17		BORING TYPE Wash	
DRILLER C. Dean		SOIL ENGINEER A. Dean		GROUND ELEV	
LEGEND					
<div style="display: flex; justify-content: space-between;"> <span>■ - Core</span> <span>⊗ - Penetration Sample</span> <span>⏏ - No Recovery</span> <span>J-Jar</span> </div> <div style="display: flex; justify-content: space-between;"> <span>▽ - Static Water Table</span> <span>▼ - Hydrostatic Water Table</span> </div>					
DESCRIPTION OF STRATUM					
Depth in Feet	Sample Type & Sample No	Penetration Reading, 1st	Blows / Foot	Description	
				Hard dark gray clay with small shell 57'	
				Sandstone 57.2'	
60	1664	4+		Hard dark gray sandy clay with shells	
65					
70				70'	
75				Hard dark gray clay -with thin sand layers	
80	1665	4+		-with sand seams	
85					
90					
95				93'	
				Sandstone 93.2'	
100	1666	4+		Hard dark gray clay with silt seams	
105				Bottom @ 101'	

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LOG OF BORING					
PROJECT <b>Underground P.O.L. Storage Cavity</b>			BORING NO <b>CB-4</b>		
CLIENT <b>United States Air Force</b>			LOCATION <b>North Bryan Test Cavity Site</b>		
DATE <b>5-8 70</b>		JOB NO <b>70-17</b>	BORING TYPE <b>Rotary</b>		GROUND ELEV
DRILLER <b>C. Dean</b>		SOIL ENGINEER <b>A. Dean</b>			
LEGEND					
<input type="checkbox"/> - Core <input checked="" type="checkbox"/> - Penetration Sample <input checked="" type="checkbox"/> - No Recovery    J Jar <input type="checkbox"/> - Static Water Table <input type="checkbox"/> - Hydrostatic Water Table					
DESCRIPTION OF STRATUM					
Depth in Feet	Sample Type	Sample No	Penetrometer Reading, lbf	Blows / Foot	
		1668	4+		Hard dark gray sandy clay with grass roots
		1669	4+		-becomes tan and gray with calcareous nodules
5		1670	4+		-becomes hard tan clay with calcareous nodules
		1671	4+		-with iron ore streaks
		1672	4+		
10		1673	4+		-becomes tan and gray with sandy silt layer, shell, sand pockets and iron ore
		1674	4+		-becomes tan and dark gray with sand seams, iron ore and shell
15		1675	4+		-becomes dark gray with silt seams, sand seams and shell
		1676	4+		-becomes slickensided
		1677	4+		
		1678	4+		
		1679	4+		-with silty sand pockets and 1/2" shell layer
20		1680	4+		-with shell
		1681	4+		-with silt seams
		1682	4+		
		1683	4+		
25		1684	4+		-with sandy clay layers and shell
		1685	4+		-with shell
		1686	4+		
		1687	4+		

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LOG OF BORING					
PROJECT		Underground P.O.L. Storage Cavity		BORING NO CB-4	
CLIENT		United States Air Force		LOCATION North Bryan Test Cavity Site	
DATE 5-8-70		JOB NO 70-17		BORING TYPE Rotary	
DRILLER C. Dean		SOIL ENGINEER A. Dean		GROUND ELEV	
LEGEND					
<div style="display: flex; justify-content: space-between;"> <span>■ - Core</span> <span>⊗ - Penetration Sample</span> <span>□ - No Recovery</span> </div> <div style="display: flex; justify-content: space-between;"> <span>▽ - Static Water Table</span> <span>▼ - Hydrostatic Water Table</span> </div>					
DESCRIPTION OF STRATUM					
Depth in Feet	Sample Type & Sample No	Penetrometer Reading, lbf	Blows / Foot	Description	
	1688			Hard dark gray clay with shell 28.5'	
				Sandstone with 2 small clay layers 30'	
30	1689	4+		Hard dark gray sandy clay with shell and trace of calcareous nodules	
	1690	4+		-becomes brown and dark gray with clay layer and shell	
	1691	4+		-becomes hard dark gray clay with silt seams and shell	
	1692	4+			
	1693	4+		-becomes hard dark gray sandy clay with shell	
35	1694	4+			
	1695	4+		-becomes silty clay with white clay streaks	
	1696	4+			
	1697	4+		-becomes hard dark gray clay with sand seams and shell	
	1698	4+			
40	1699	4+		-with shell, clay layers and clay streaks, slickensided	
	1700	4+			
	1701	4+		-with silt seams and shell	
	1702	4+		-becomes hard dark gray sandy clay with shell	
45	1703	4+			
	1704	4+			
	1705	4+		-with trace of organic matter	
	1706	4+		-with shell and gray clay layer	
	1707	4+		-becomes hard dark gray clay with silty sand layer @ 48.5'	
50	1708	4+		-with silt seams, silty clay layer and sand layer from 49.5' to 50'	
	1709	4+		-becomes very stiff dark gray sandy clay with brown clay layers, silt seams and silt layers	
	1710	4+		-becomes hard dark gray and brown clay with silt seams	
	1711	4+		-with sandy silt layer	
	1712	4+		-with silty sand layer and silt seams	
55	1713	4+		-becomes gray clay with small sand layers	

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LOG OF BORING					
PROJECT		Underground P.O.L. Storage Cavity		BORING NO CB-4	
CLIENT		United States Air Force		LOCATION North Bryan Test Cavity Site	
DATE 5-13-70		JOB NO 70-17		BORING TYPE Rotary	
DRILLER C. Dean		SOIL ENGINEER A. Dean		GROUND ELEV	
LEGEND					
<div style="display: flex; justify-content: space-between;"> <span>■ - Core</span> <span>⊞ - Penetration Sample</span> <span>⚡ - No Recovery</span> <span>J-Jar</span> </div> <div style="display: flex; justify-content: space-between; margin-top: 5px;"> <span>▽ - Static Water Table</span> <span>▽ - Hydrostatic Water Table</span> </div>					
DESCRIPTION OF STRATUM					
Depth, in Feet	Sample Type	Sample No	Penetrometer Reading, lbf	Blows / Foot	Description
		1714	2.5		Hard gray clay with small sand layers  -becomes very stiff with sand layers, silt seams and clay layers
		1715	2.5		
60					
		1717			-becomes alternate layers of sand, silt and clay
65		1718			
		1719			
		1720	4+		-becomes hard gray clay with silt and sand laminations
70		1721	4+		
		1722	4+		-with silt laminations
		1723	4+		
75		1724	4+		-becomes hard gray silty clay with clay layers and silt seams
		1725	4+		
		1726	4+		-with silty fine sand layer
80		1727	4+		
<hr style="width: 50%; margin: 10px auto;"/> Bottom @ 80'					

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## Preliminary

SUMMARY OF LABORATORY TEST DATA														
PROJECT Underground P.O.L. Storage Cavity														
JOB NO 70 - 17 DATE 5-16-70														
BORING NO	DEPTH IN FEET	SAMPLE NO	TYPE OF MATERIAL	MOISTURE CONTENT %	DRY DENSITY $\rho_d$	ATTERBERG LIMITS			COMPRESSION	STRAIN %	LATERAL PRESSURE $\sigma_3$	TYPE FAILURE	OTHER TESTS	
						LL	PL	PI						
CB-4	4-6	1670	Tan clay with calcareous nodules	20	108	57	19	38	6.64	5.0	3	30° S		
	10-12	1673	Tan clay with sand seams	24	99	55	24	31	6.25	5.3	5	V-Split		
	15-16	1676	Dark gray clay, slickensided	26	97	59	23	36	3.82	4.3	8	45° S	Specific Gravity 2.682	
20-21	1681		Gray clay with silt seams	31	95	69	25	44	3.99	6.0	10	V-Split		
25-26	1685		Dark gray clay with shell	27		63	22	41						
30-31	1689		Gray sandy clay with shell fragments	26	100	39	24	15	5.53	6.7	15	60° S		
35-36	1694		Dark gray sandy clay with shell	24		30	24	6					H=1.0 x 10 <sup>-4</sup> cm/sec V=3.3 x 10 <sup>-6</sup> cm/sec Specific Gravity 2.687	
40-41	1699		Dark gray clay, slickensided	32	90	60	32	28	3.91	7.3	20	30° S		
45-46	1704		Dark gray sandy clay with shell	27		42	25	17						
50-51	1709		Gray sandy clay with silt seams	26	99	47	21	26	3.84	4.7	25	45° S	H=2.0 x 10 <sup>-6</sup> cm/sec V=1.5 x 10 <sup>-8</sup> cm/sec Specific Gravity 2.652	
54-56	1713		Gray clay with small sand layers	25		54	23	31						
57-59	1715		Gray clay with sand layers and silt seams	29		47	18	29						
63-65	1718		Gray clay with sand and silt layers	27		51	22	29					H=4.0 x 10 <sup>-4</sup> cm/sec	
7-71	1721		Gray clay with silt and sand laminations	20		44	19	25					Specific Gravity 2.694	
75-77	1725		Gray silty clay	20		40	20	20						

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